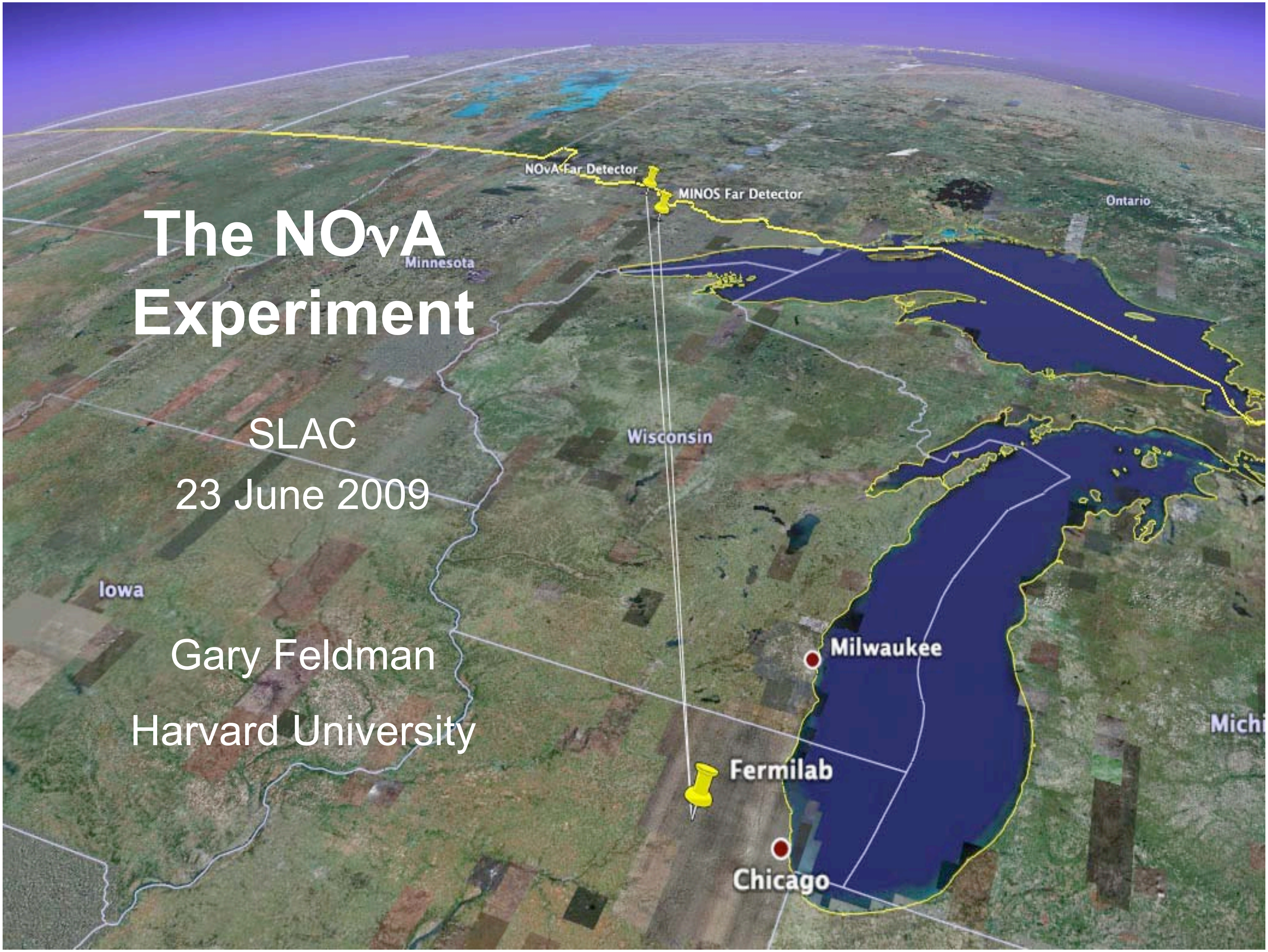
The NOνA Experiment

SLAC

23 June 2009

Gary Feldman

Harvard University



Outline

- Physics of Neutrinos and Neutrino Oscillations
- The NOνA Experiment
- More on Neutrino Oscillation Physics
- NOνA Sensitivities
- NOνA Status and Schedule

Why are Neutrinos Particularly Interesting?

- Masses are anomalously low
  - From CMB data $m_\nu < 0.2\ \text{eV}/c^2 \cong 0.0000004\ m_e$
  - A Window on the the GUT Scale? (seesaw mechanism)
- Only fundamental fermion which can be its own antiparticle (Majorana particle)
- Could be responsible for the matter/antimatter asymmetry of the universe (leptogenesis)

Seesaw Mechanism

- Right-handed neutrinos have no weak interactions and thus are not confined to the weak mass scale. Postulate both a GUT-scale right-handed Marjorana neutrino N_R and both Majorana and Dirac mass terms in the Lagrangian:

$$\mathcal{L} = \tfrac{1}{2} M_{ij} \overline{N}_{R_i} N_{R_j} + \lambda_{ij} \begin{pmatrix} \nu_L, & e_L \end{pmatrix}_i \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} N_{R_j} + \mathrm{h.c.}$$

Dropping the flavor index, this results in a mass matrix

$$\begin{pmatrix} 0 & m_l \\ m_l & M \end{pmatrix}, \quad where\ m_l = \lambda \langle \phi \rangle,$$

a “normal” fermionic mass.

Seesaw Mechanism

Diagonalizing the mass matrix to obtain the physical masses yields,

$$m_N \approx M \quad \text{and} \quad m_\nu = \frac{m_l^2}{M}.$$

This is the seesaw mechanism.

Leptogenesis

- To explain how our matter-dominated universe arose from a matter-antimatter symmetric big bang, we need (Sakharov conditions)
  - Lepton and baryon number violation
  - CP violation (Standard Model quark CP violation not sufficient)
  - Thermal non-equilibrium
- Majorana neutrinos can provide these conditions.

Leptogenesis

- CP-violating decays of *N*'s in the big bang era provides a source of lepton-number violation.
  - Example: $N \to h\nu \neq \overline{N} \to h\overline{\nu}$

- GUT-level (B - L)-conserving interactions convert the lepton-number asymmetry to a baryon asymmetry.

Neutrino Oscillations

- Neutrino oscillations occur because the weak eigenstates and not identical to the mass eigenstates.
- Neutrinos are always produced and detected in weak eigenstates, but they propagate in mass eigenstates.
- To the extent that the masses of the mass eigenstates are different, the phase relations generated by the propagation ($e^{-iEt/\hbar}$) change, producing the oscillation.

Mixing Matrix

- The relationship between the weak eigenstates and the mass eigenstates is given by a unitary rotation matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Mixing Matrix

- The mixing matrix can be specified by 3 angles and one complex phase:

$$|\nu_\ell\rangle = U|\nu_n\rangle, \quad \text{where } (c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\nu_\mu \rightarrow \nu_\tau$ **atmospheric** $\quad \nu_\mu \rightarrow \nu_e$ **atmospheric** $\quad \nu_e \rightarrow \nu_\mu, \nu_\tau$ **solar**

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\, e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\, e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\, e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\, e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Vacuum Oscillations

- When a 2 x 2 oscillation is sufficient, in vacuum,

$$i\hbar\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix},\ H = \begin{pmatrix}\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}$$

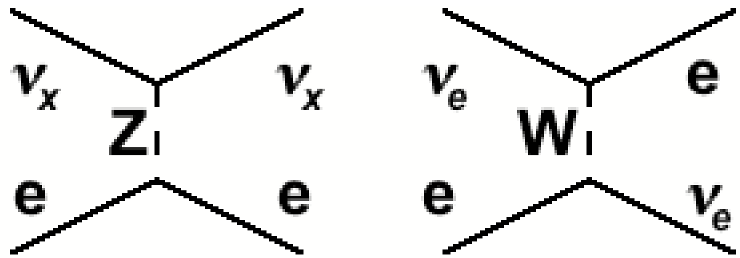
$$P(\nu_e \rightarrow \nu_x) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$$\Delta m_{ij}^2 \equiv (m_i^2 - m_j^2) \text{ in } (\mathrm{eV}/c^2)^2,$$

L in km, and E in GeV

Matter Oscillations

- Matter effects: In matter ν_e's interact differently than ν_x's.



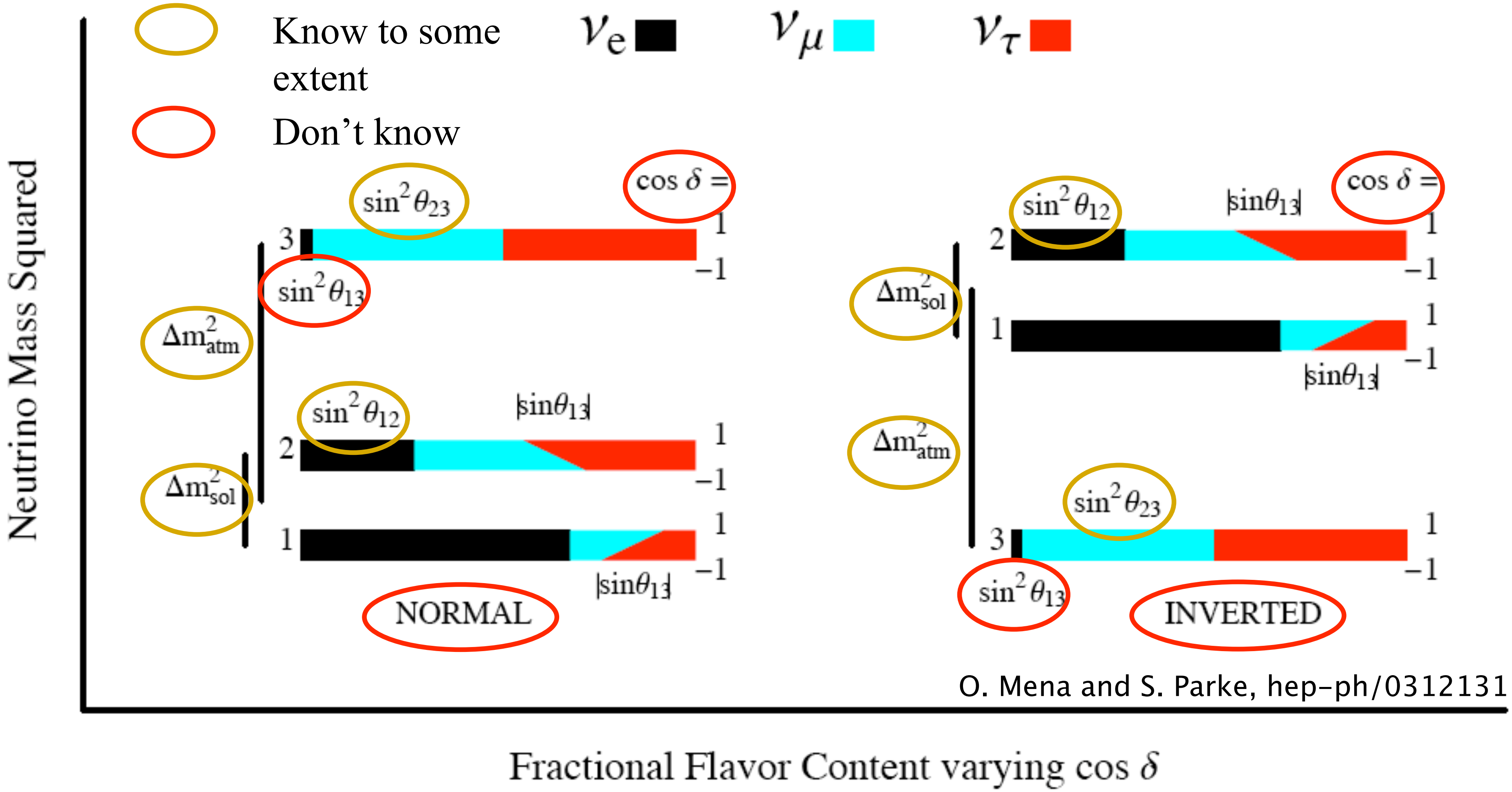
$$H = \begin{pmatrix} \frac{\Delta m^2}{4E}\cos 2\theta - \sqrt{2} G_F \rho_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\cos 2\theta - \sqrt{2} G_F \rho_e E / \Delta m^2)^2 + \sin^2 2\theta}$$

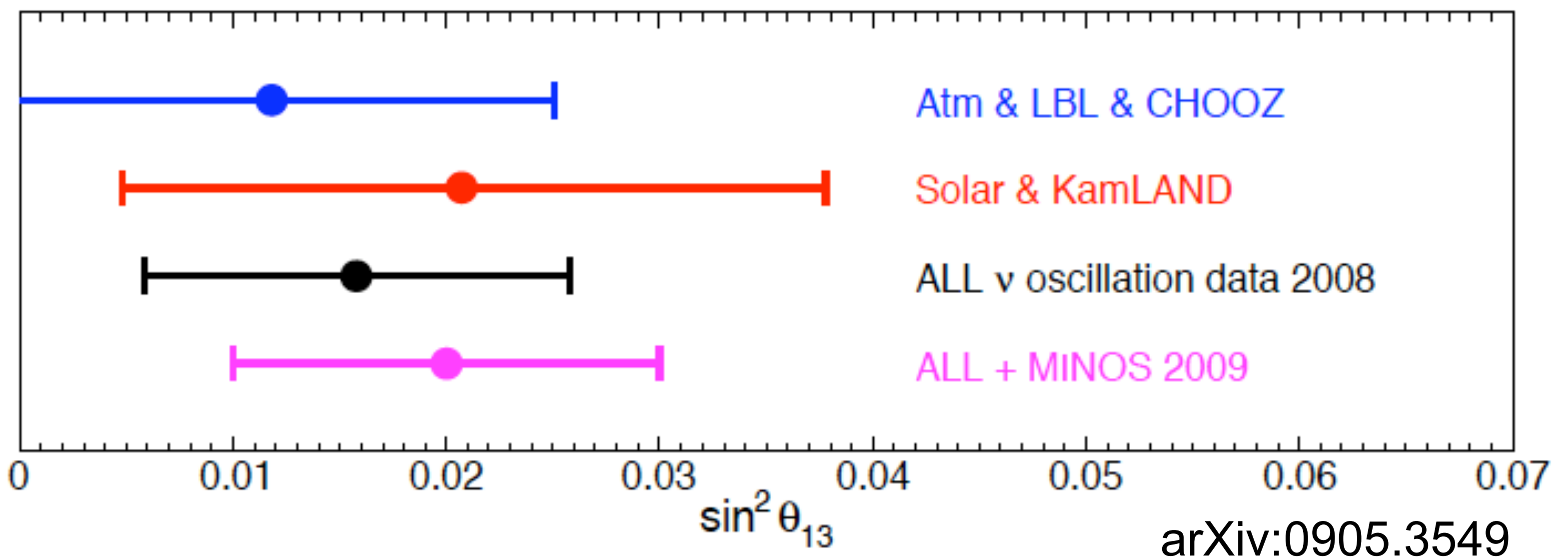
What Have We Learned?

- From observing neutrinos from the sun and reactors, we have learned that $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$ with *L/E* ≈ 15 000 km/GeV, with a large but not maximal mixing angle, θ_{12}.
- From observing neutrinos produced in the atmosphere by cosmic rays and 1st generation accelerator experiments (K2K and MINOS) we have learned that $\nu_\mu \rightarrow \nu_\tau$ with *L/E* ≈ 500 km/GeV, with a mixing angle, θ_{23}, consistent with being maximal.

What We Know and What We Don't Know



Fogli et al. Global Fit to Data on θ_{13}



arXiv:0905.3549

Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.

- $\theta_{13} = 0$ disfavored by $\sim 2\sigma$
- Central value $\sin^2\theta_{13} = 0.02$ or $\sin^2(2\theta_{13}) = 0.08$

A Digression: Some Physics from String Theory

- I usually do not pay attention to theoretical predictions in this field because they are usually not based on anything more than numerology. However, a colleague of mine, Cumrun Vafa and his students have recently done some work that I find quite interesting.
- They have used string theory and two simple assumptions to make no-free-parameter first-order estimates of the quark and lepton mixing matrices. And the CKM predictions are dead-on.
- The references are [hep-th] arXiv:0811.2417 (quarks), [hep-ph] arXiv:0904.1419 (leptons), and [hep-th] arXiv:0904.3101 (CP violation).

Assumptions

- The assumptions:
  - A GUT exists.
  - Particle physics is not changed in the absence of gravity (i.e., the Planck mass $\rightarrow \infty$).
- Surprisingly, with these assumptions, both string theory and possible GUTs become quite restrictive.
- The only parameter is α_{GUT} and this is determined from running the measured coupling constants to the GUT scale: $\alpha_{GUT} = 0.04$.

Quark Predictions

- For the quarks, the CKM matrix is estimated to be

$$V_{CKM} \approx \begin{pmatrix} 1 & \alpha_{GUT}^{1/2} & \alpha_{GUT}^{3/2} \\ \alpha_{GUT}^{1/2} & 1 & \alpha_{GUT} \\ \alpha_{GUT}^{3/2} & \alpha_{GUT} & 1 \end{pmatrix} = \begin{pmatrix} 1 & 0.2 & 0.008 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

compared to the measured values

$$\begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 0.99 \end{pmatrix}$$

Neutrino Predictions (1)

- Leptons are different from quarks due to the GUT-level right-handed neutrino. (But some Dirac models give the same results).
- Predictions:
  - Normal mass ordering with $(m_1, m_2, m_3) \propto (\alpha_{GUT}, \alpha_{GUT}^{1/2}, 1)$.
    - $\Rightarrow \Delta m^2_{atm} \approx 30\ \Delta m^2_{sol}$. Data = 31±2.
    - $\Rightarrow m_1 \approx 0.002$ eV. Probably unmeasurable.

Neutrino Predictions (2)

- The PMNS matrix is predicted to be

$$V_{PMNS} \approx \begin{pmatrix} U_{e1} & \alpha_{GUT}^{1/4} & \alpha_{GUT}^{1/2} \\ \alpha_{GUT}^{1/4} & U_{\mu 2} & \alpha_{GUT}^{1/4} \\ \alpha_{GUT}^{1/2} & \alpha_{GUT}^{1/4} & U_{\tau 3} \end{pmatrix}$$

  - $\Rightarrow \theta_{23} \approx \theta_{12} \approx 27^{o}.\quad \text{Data}: \theta_{12} = 34 \pm 1^{o}; \theta_{23} = 45 \pm 7^{o}.$
  - $\Rightarrow \theta_{13} \approx \theta_{C} \approx 12^{o} \Rightarrow \sin^{2}(2\theta_{13}) \approx 0.15.$

Neutrino Predictions (3)

- The Jarlskog invariant, J ,

$$J = \frac{1}{8}\sin^2(2\theta_{12})\sin^2(2\theta_{13})\sin^2(2\theta_{23})\cos(\theta_{13})\sin(\delta)$$

is an invariant measure of CP violation.

- Vafa's predictions:

$$|J_{quark}| \approx \alpha_{GUT}^3 \approx 6 \times 10^{-5}$$

$$|J_{lepton}| \approx \alpha_{GUT} \approx 4 \times 10^{-2}$$

- For both quarks and leptons, these values imply $|\sin(\delta)| \approx 1$, which agrees well with the quark measurement of $\sin(\delta) = 0.93$.

NOνA: NuMI Off-Axis ν_e Appearance Experiment

- NOνA is a second-generation 2-detector experiment on the NuMI beamline.
- It is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ oscillations.
  - It will give an order of magnitude improvement over MINOS in measurements of ν_e appearance and ν_μ disappearance.
- The NOνA detectors are "totally active" tracking liquid scintillator calorimeters, sited off-axis to take advantage of a narrow-band beam.
- The NOνA project also includes accelerator upgrades to bring the beam power from 400 kW to 700 kW.
- NOνA's unique feature is its long baseline (810 km), which gives it sensitivity to the neutrino mass ordering.
- NOνA is complementary to both T2K and Daya Bay.

The NOνA Collaboration

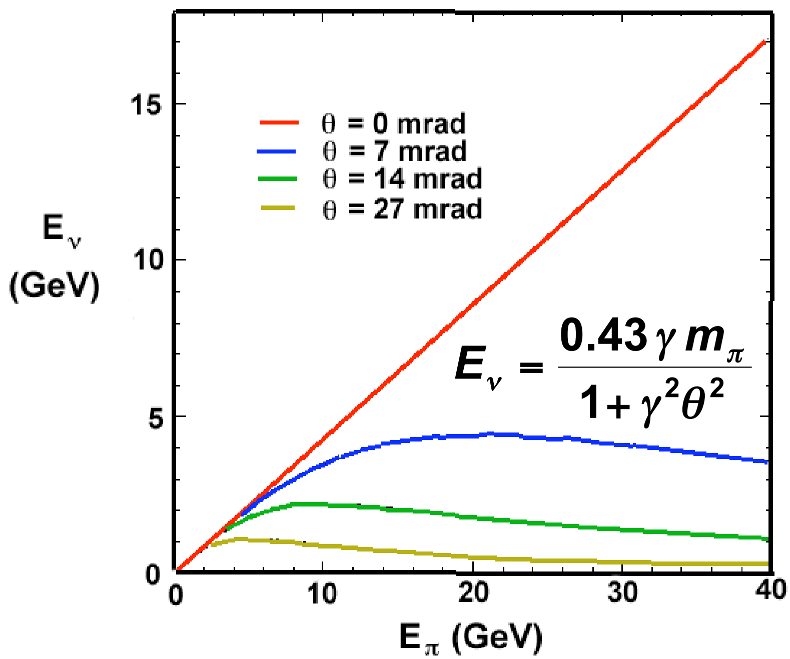
at Argonne National Lab, 25 April 2009

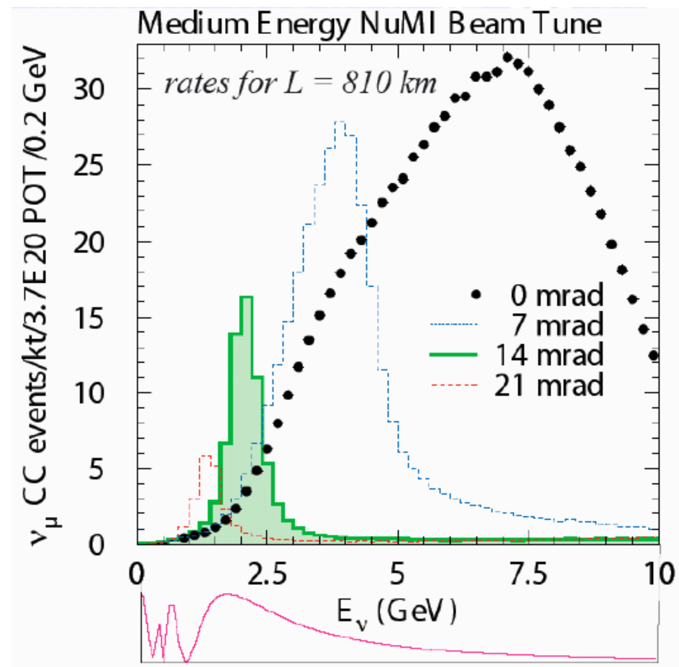
180 Scientists and Engineers from 26 Institutions

Argonne National Laboratory - University of Athens - California Institute of Technology - University of California, Los Angeles - Fermi National Accelerator Laboratory - Harvard University - Indiana University - Lebedev Physical Institute - Michigan State University - University of Minnesota, Duluth - University of Minnesota, Minneapolis - The Institute for Nuclear Research, Moscow - Technische Universität München, Munich - State University of New York, Stony Brook - Northwestern University - University of South Carolina, Columbia - Southern Methodist University - Stanford University - University of Tennessee - Texas A&M University - University of Texas, Austin - University of Texas, Dallas - Tufts University - University of Virginia, Charlottesville - The College of William and Mary - Wichita State University

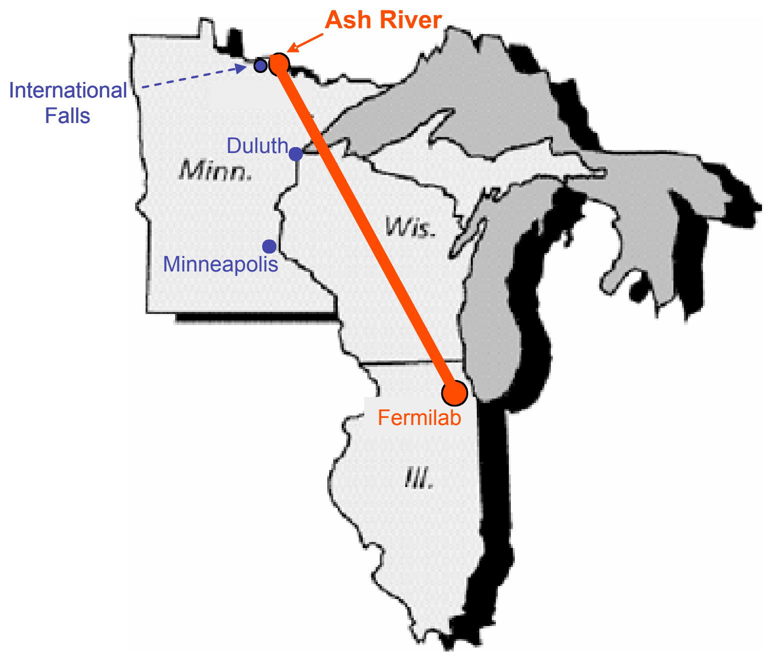
Why Off-Axis?

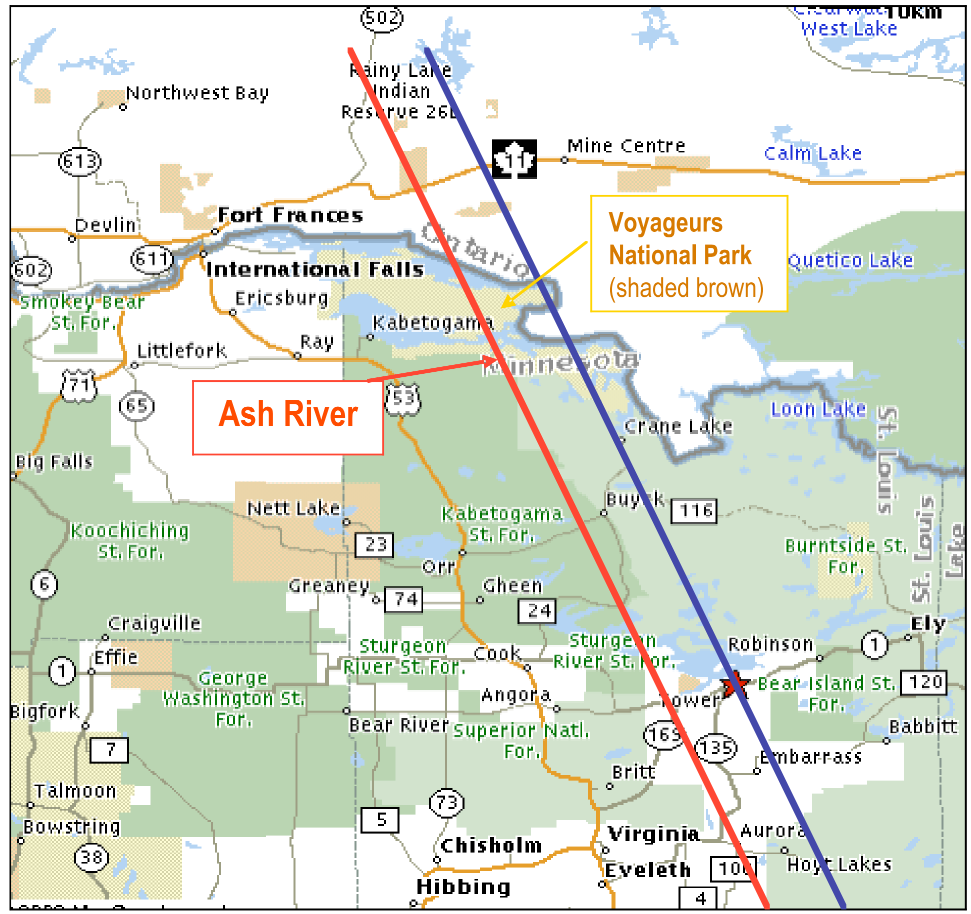
- Both Phase 2 experiments, NOνA and T2K are sited off the neutrino beam axis. This yields a narrow band beam:
  - More flux and less background (ν_e's from *K* decay and higher-energy NC events)





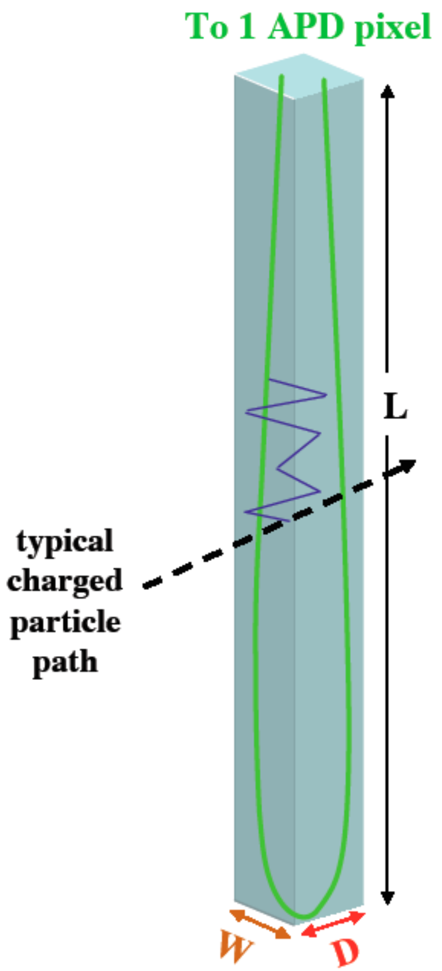
Why Ash River for the Far Detector?





The Ash River site is the furthest available site from Fermilab along the NuMI beamline. This maximizes NOνA's sensitivity to the mass ordering.

NOvA Basic Detector Element

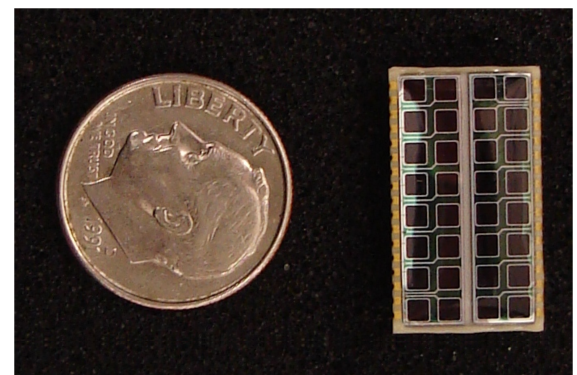


Liquid scintillator in a 4 cm wide, 6 cm deep, 15.7 m long, highly reflective PVC cell.

Light is collected in a U-shaped 0.7 mm wavelength-shifting fiber, both ends of which terminate in a pixel of a 32-pixel avalanche photodiode (APD).

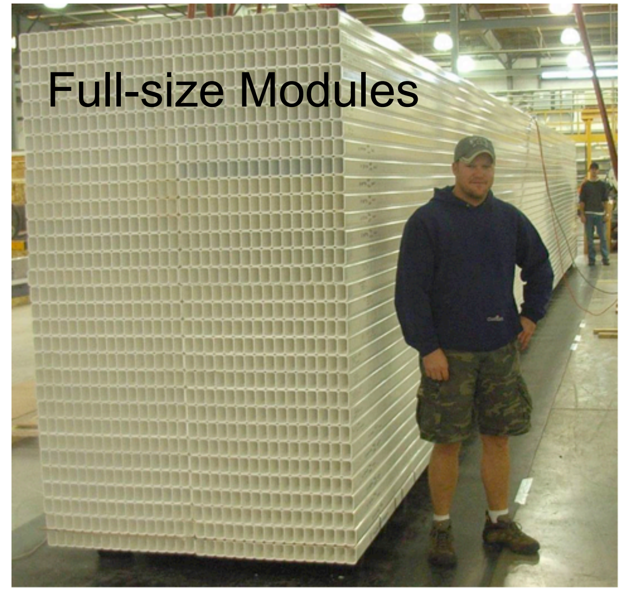
The APD has peak quantum efficiency of 85%. It will be run at a gain of 100. It must be cooled to -15°C and requires a very low noise amplifier.


Fiber Stringing Machine



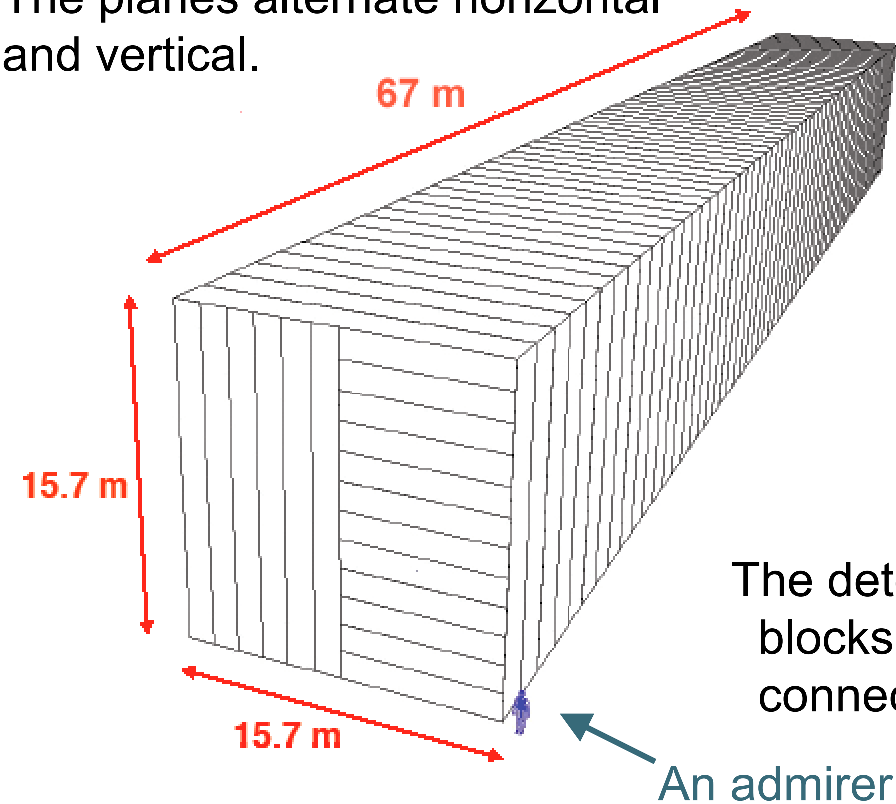
32-cell APD

Far Detector



The cells are made from 32-cell extrusions.

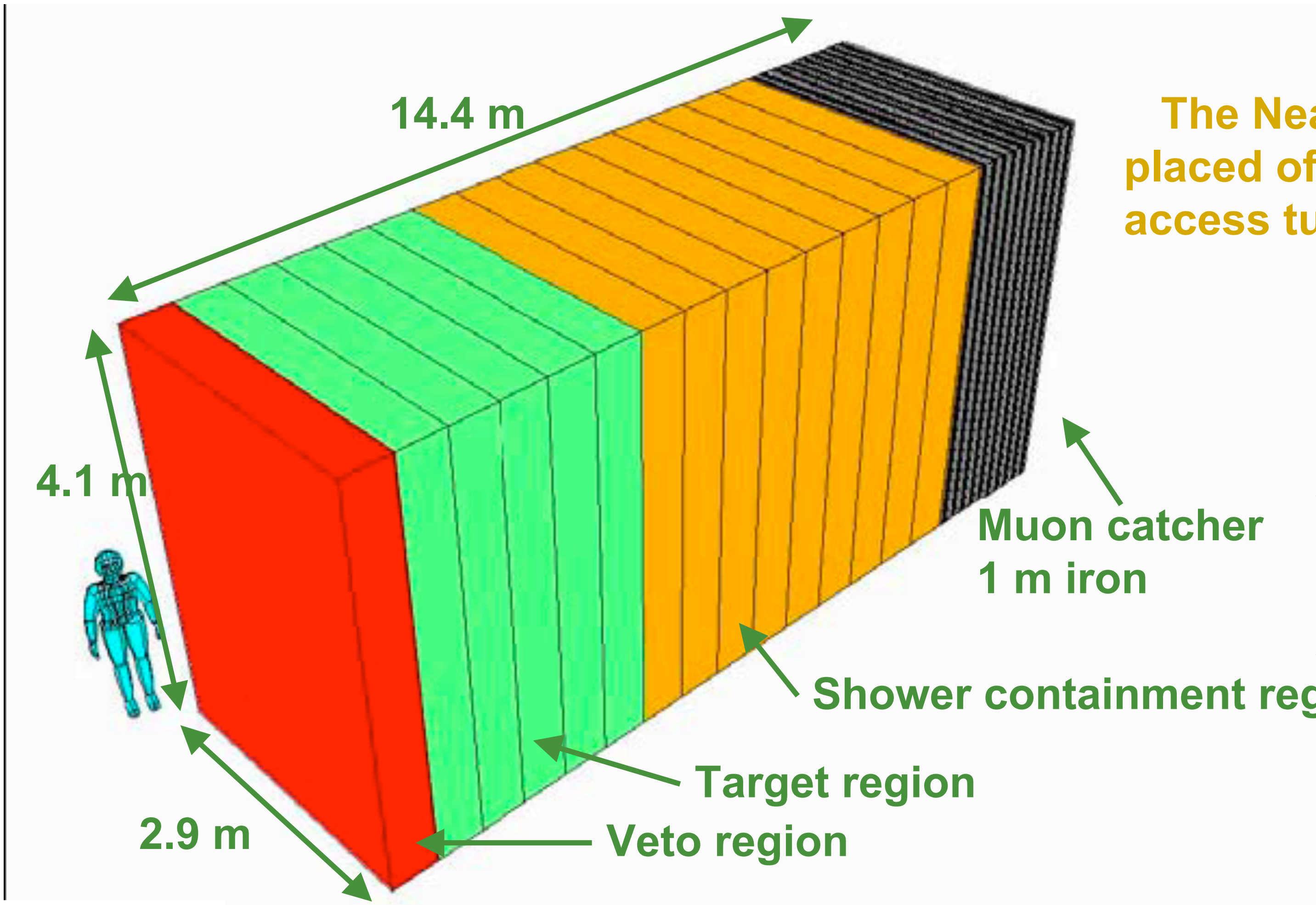
12 extrusion modules make up a plane. The planes alternate horizontal and vertical.



There are 1003 planes, for a total mass of 15 kT. There is enough room in the building for 18 kT, which can be built if we can preserve half of our contingency.

The detector can start taking data as soon as blocks are filled and the electronics connected.

The Near Detector



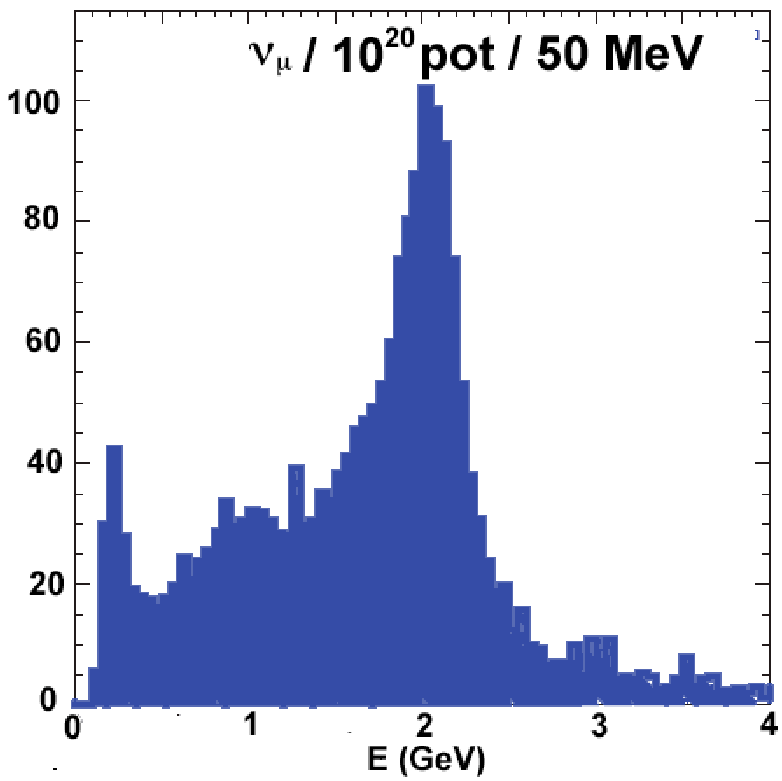
The Near Detector will be placed off-axis in the MINOS access tunnel.

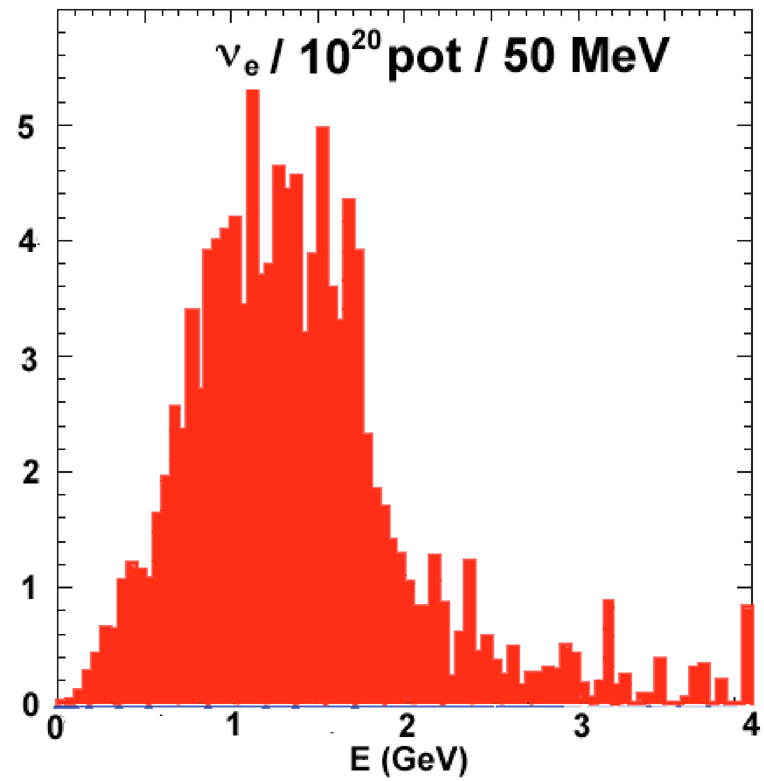
209 T
126 T totally active
23 T fiducial

The Integration Prototype Near Detector

We plan to build the Near Detector and have it running near the MINOS surface building at Fermilab next year.

It will detect a 107 mr off-axis NuMI beam, dominated by *K* decays.

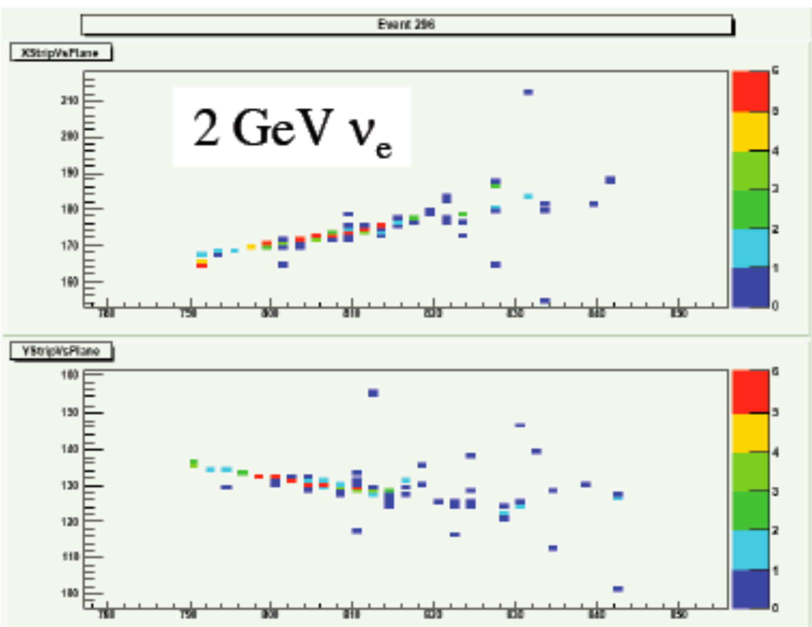


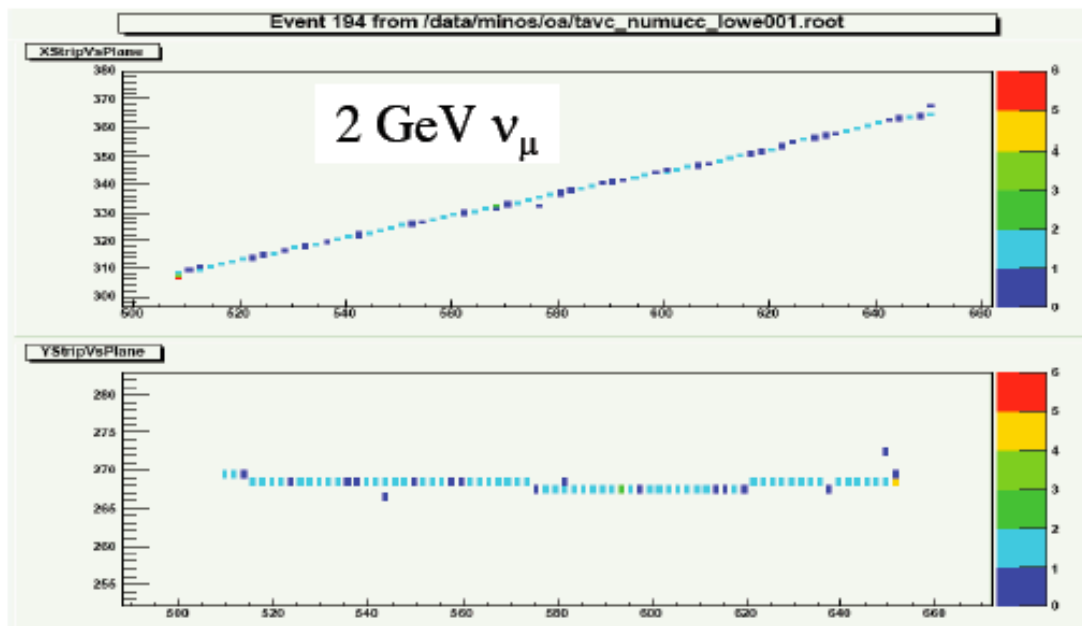


Event Quality

Longitudinal sampling is ~0.2 X_0, which gives excellent μ-*e* separation.

A 2-GeV muon is 60 planes long.





ν_e CC event

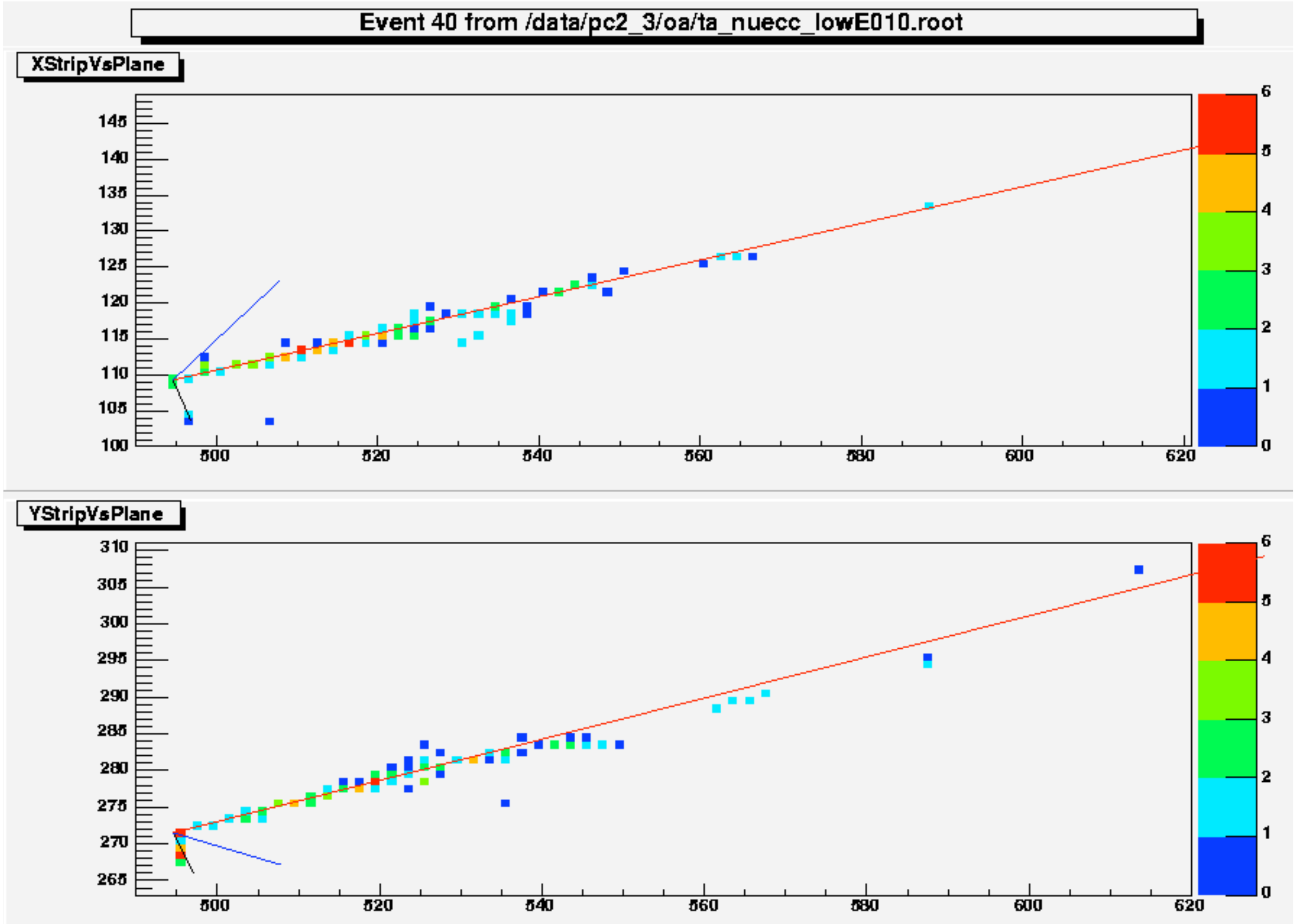
$\nu_e p \rightarrow e^- p \pi^+$

E_ν=2.5GeV

E_e=1.9GeV

E_p=1.1GeV

E_π=0.2GeV



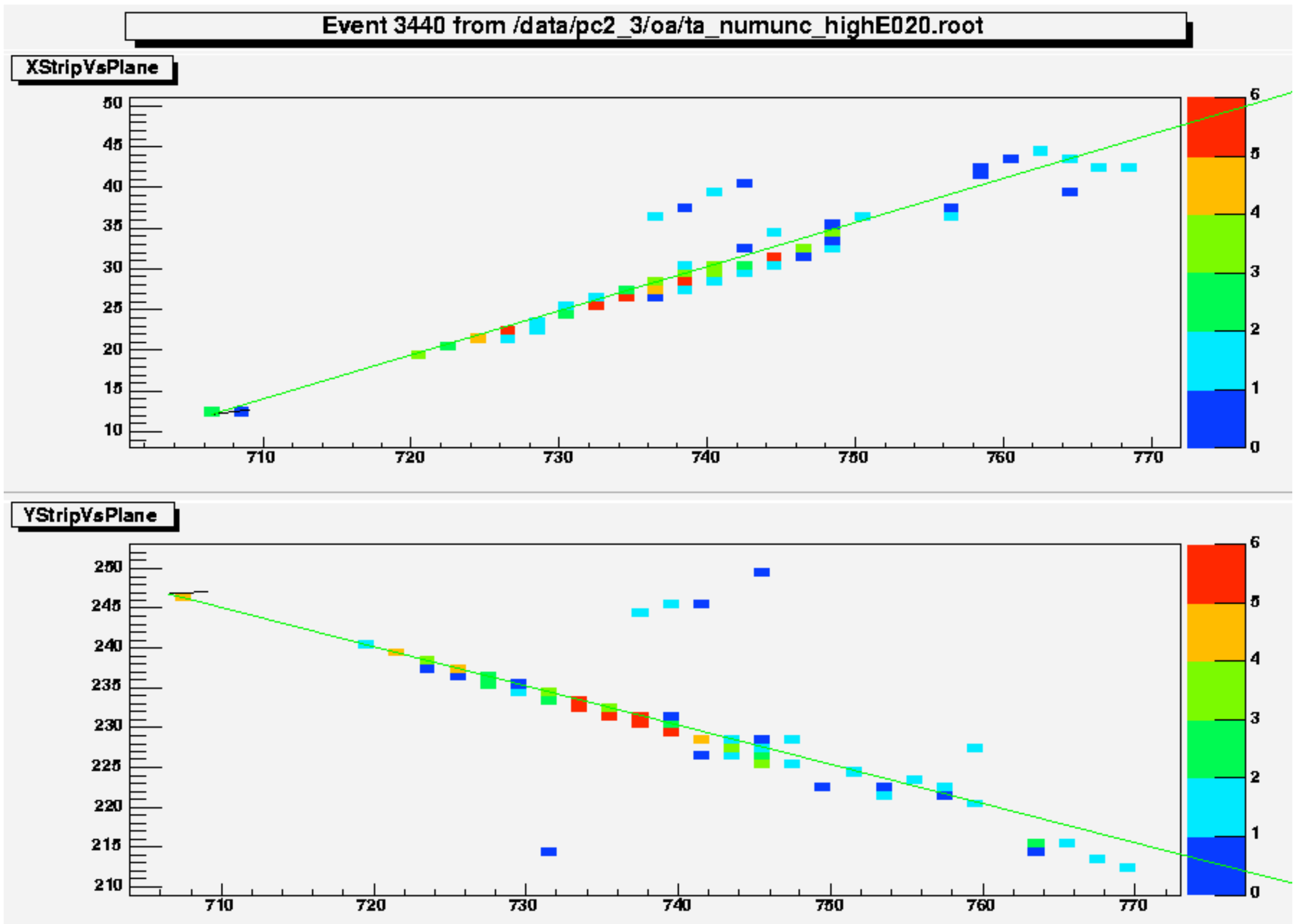
Background NC event

$\nu_\mu N \rightarrow \nu_\mu p \pi^o$

E_ν=10.6 GeV

E_p=1.04GeV

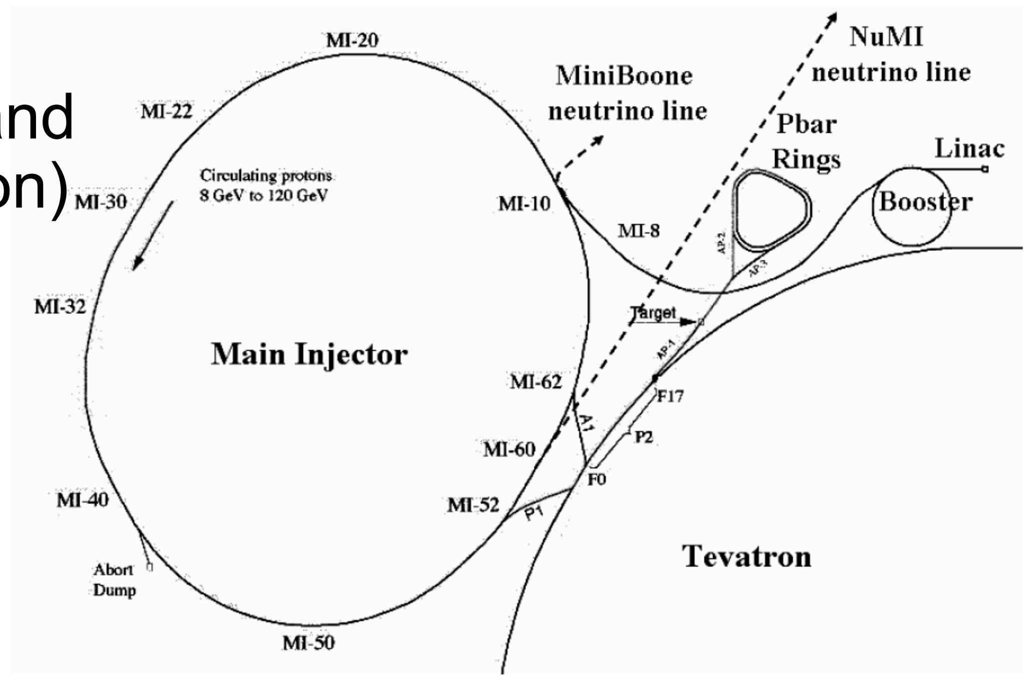
$E_{\pi o}$ =1.97GeV



Present Beam Operation

- The Booster injects 11 batches (9 for NuMI and 2 for antiproton production) into the Main Injector at 15 Hz.

  The Main Injector then ramps up, extracts the beam and ramps down for a cycle time of 2.2 s.



The NOνA Beam Upgrade

- Use the 8-GeV Recycler Ring, which sits above the Main Injector ring to store 12 Booster batches while the Main Injector ramps.
- Inject the Recycler beam in a single turn into the Main Injector.
- Increase the ramp rate of the Main Injector to obtain a cycle time of 1.33 s.

$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$
  - $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$ "Atmospheric"
  - $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{12}^2\ L/E)$ "Solar"
  - $P_3 = \mp J \sin(\delta) \sin(1.27\ \Delta m_{13}^2\ L/E)$
  - $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{13}^2\ L/E)$

  $\left.\begin{array}{l} P_3 \\ P_4 \end{array}\right\}$ Atmospheric-solar interference

  where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \times$

  $\sin(1.27\ \Delta m_{13}^2\ L/E) \sin(1.27\ \Delta m_{12}^2\ L/E)$

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

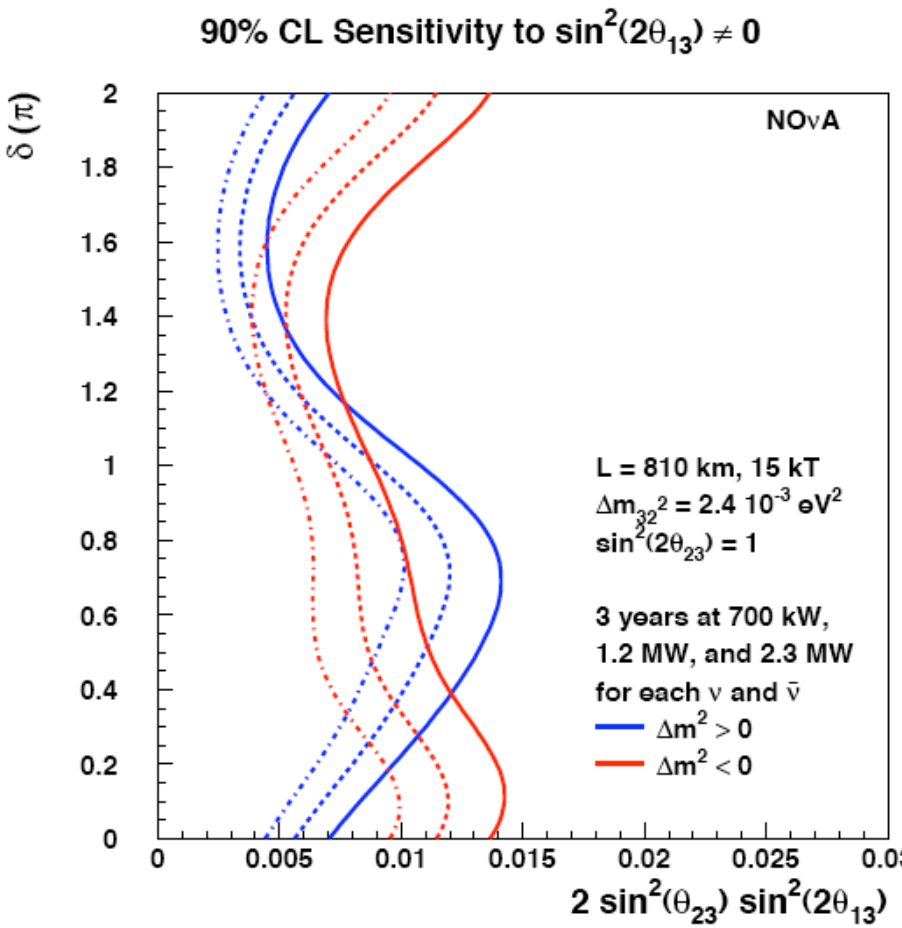
- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy.

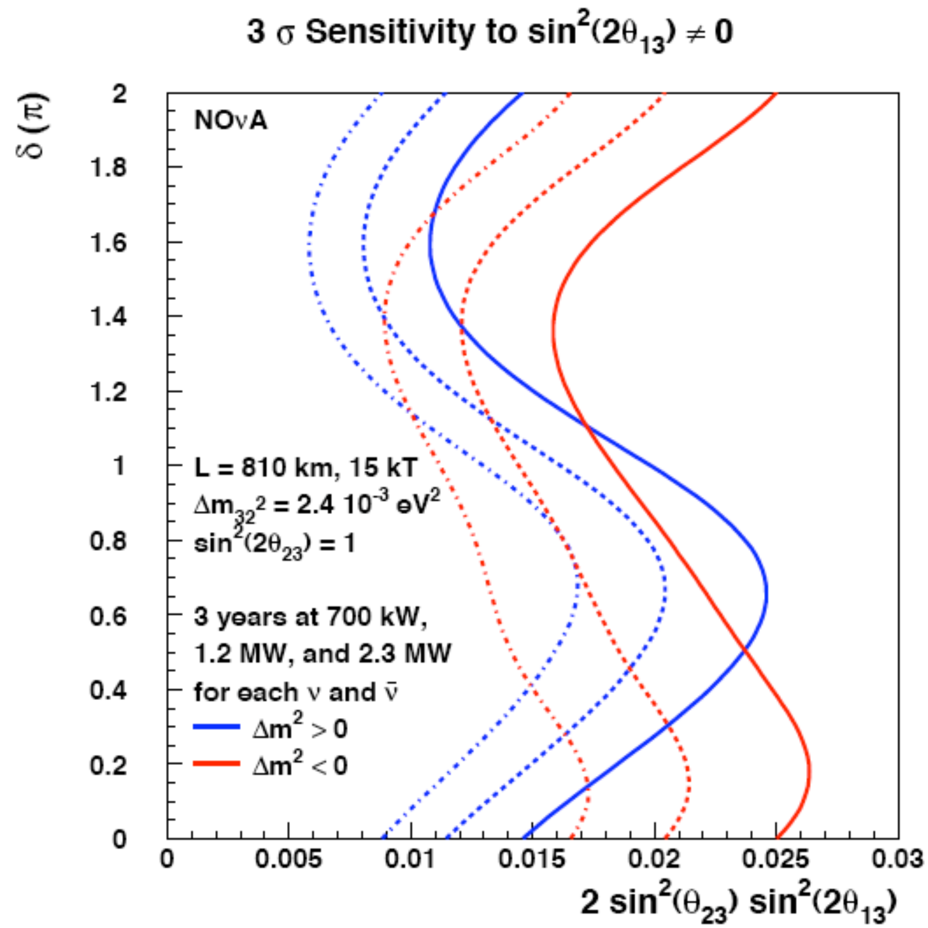
$$E_R = \frac{\Delta m^2_{13}}{2\sqrt{2}G_F\rho_e} \approx 11\,\text{GeV for the earth's crust.}$$

About a ±30% effect for NuMI, but only a ±11% effect for T2K.

However, the effect is reduced for energies above the oscillation maximum and increased for energies below.

Sensitivity to $\sin^2(2\theta_{13}) \neq 0$

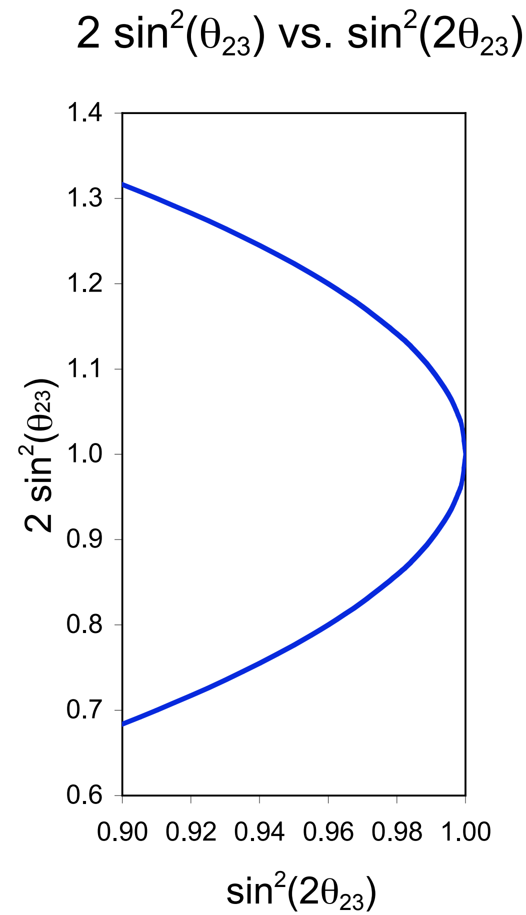




Reactor vs. Accelerator

Reactor and accelerator experiments do not measure the same thing. Reactors are sensitive to $\sin^2(2\theta_{13})$, while accelerators are mostly sensitive to $\sin^2(\theta_{23})\ \sin^2(2\theta_{13})$.
If $\theta_{23} \neq \pi/4$, these quantities can be quite different.

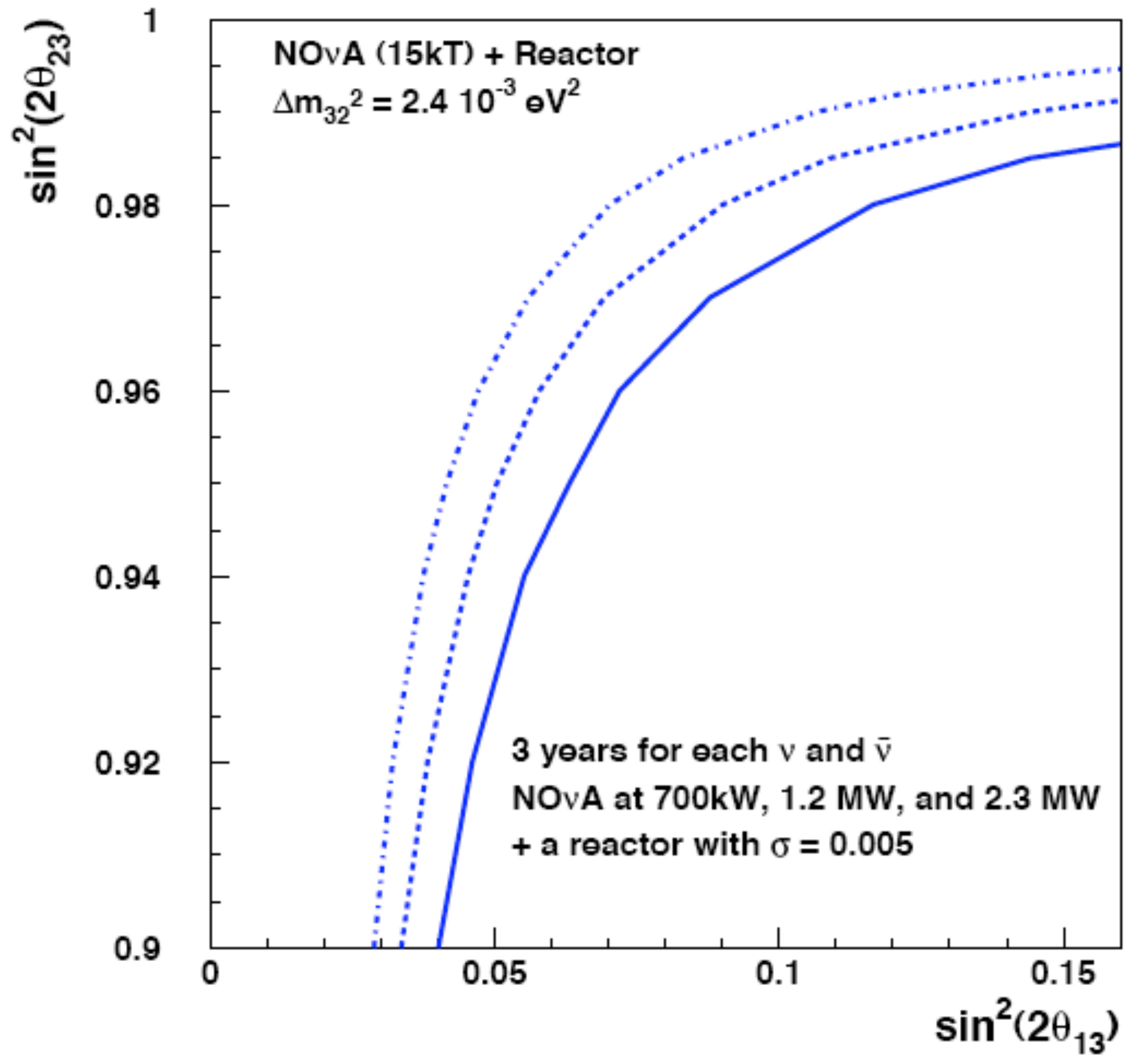
The good news is that a comparison of NOνA and Daya Bay can break this ambiguity and determine whether ν_3 couples more to ν_μ or ν_τ.



95% CL Resolution of the θ_{23} Ambiguity

The ambiguity can be resolved in the region below and to the right of the curves.

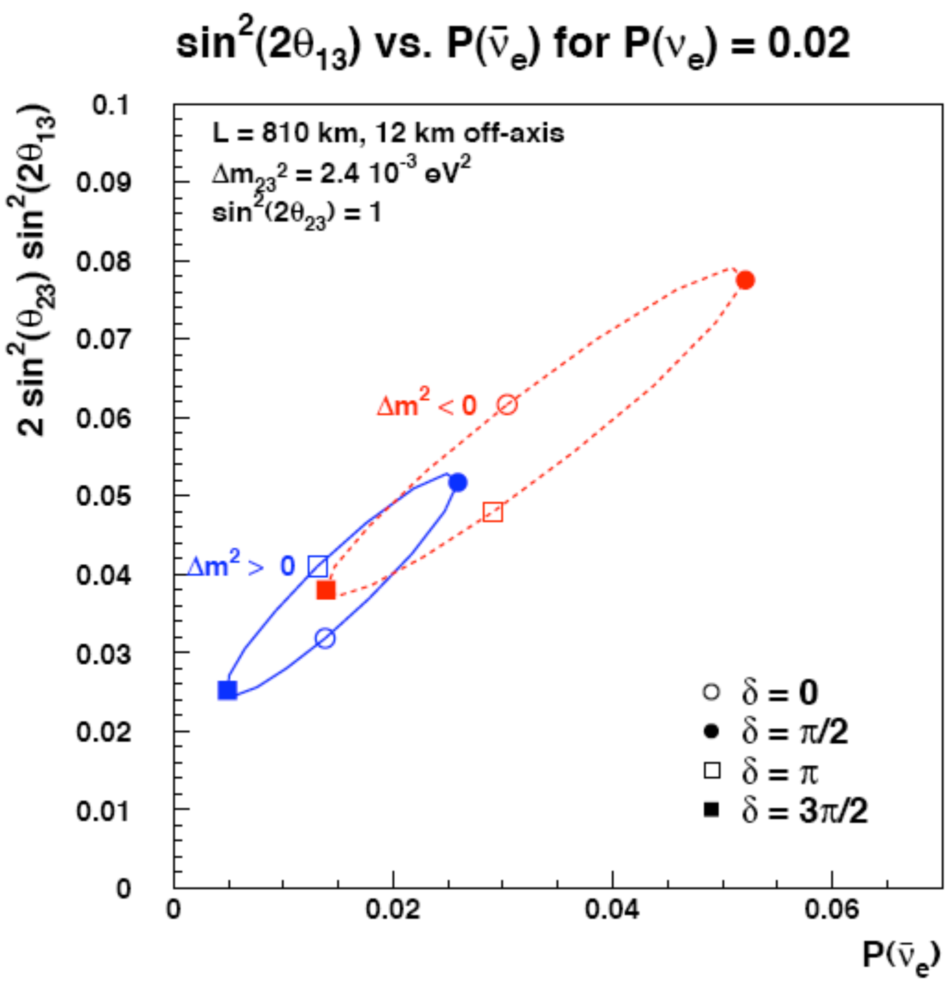
The sensitivity depends on the mass ordering, δ, and the sign of the ambiguity itself. The curves represent an average over these parameters.



Importance of the Mass Ordering

- Window on very high energy scales: grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- To measure CP violation, we need to resolve the mass ordering, since it contributes an apparent CP violation that we must correct for.

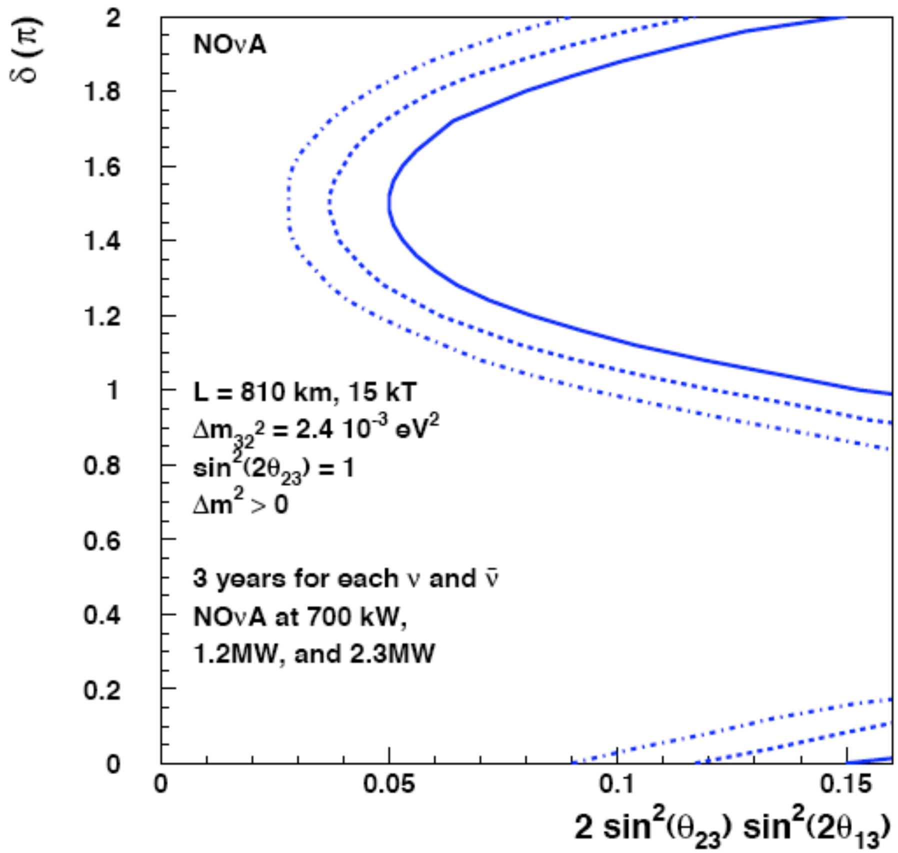
Parameters Consistent with a 2% $\nu_\mu \rightarrow \nu_e$ Oscillation Probability



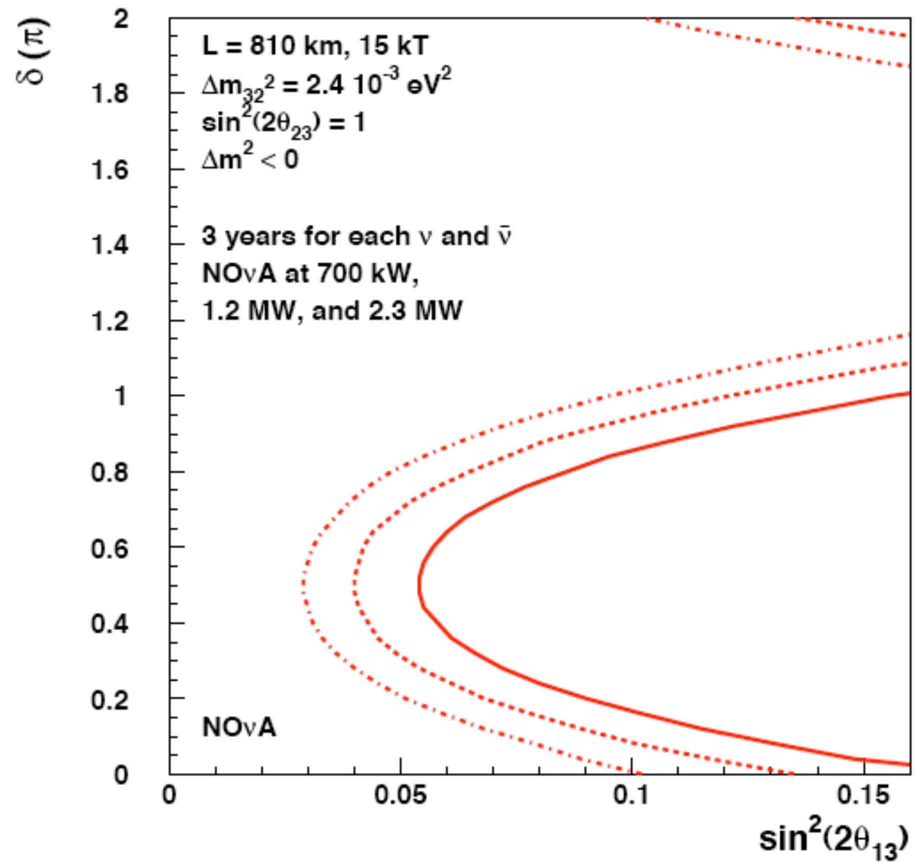
Strategy for Determining the Mass Ordering

- If the CP-violating term goes in the same direction as the matter effect, then there is no ambiguity and NOνA can determine the mass ordering by itself, given sufficient integrated beam.
- If the CP-violating term goes in the opposite direction as the matter effect, then there is an inherent ambiguity and NOνA cannot determine the mass ordering by itself. But it can be determined, in principle, by comparing NOνA and T2K.
  - If the neutrino oscillation probability is larger in NOνA than in T2K, it is the normal mass ordering; if the opposite, it is the inverted mass ordering.

95% CL Resolution of the Mass Ordering NOνA Alone

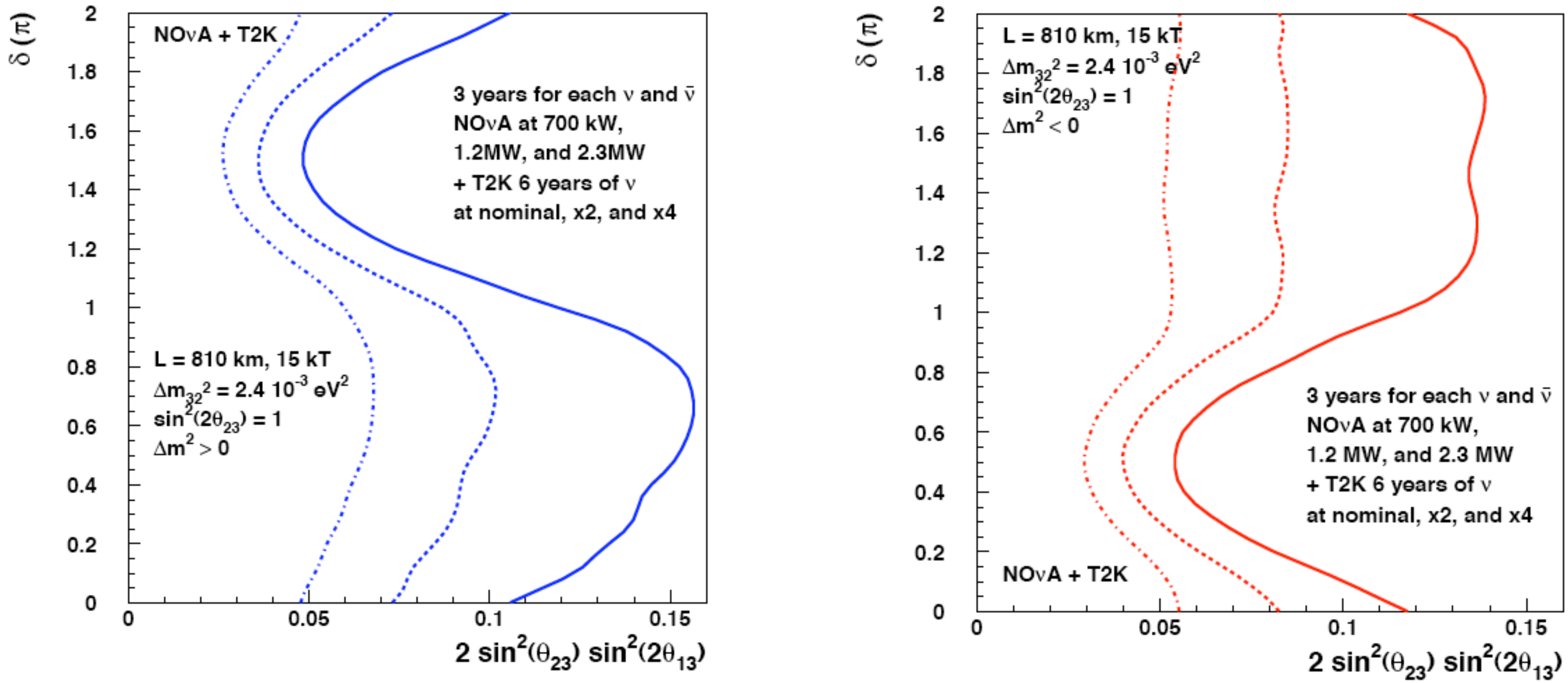


Normal Ordering



Inverted Ordering

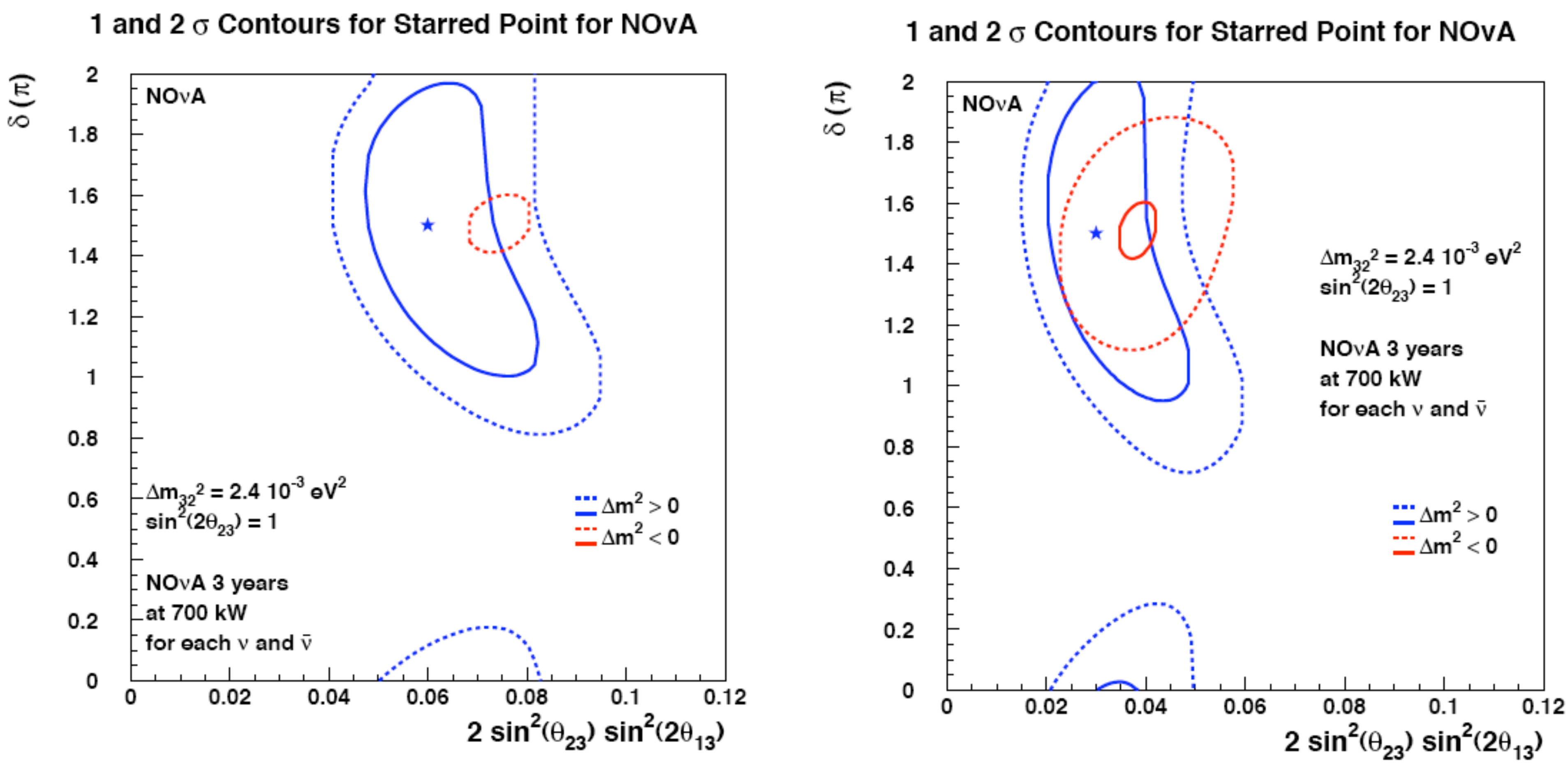
95% CL Resolution of the Mass Ordering NOνA Plus T2K



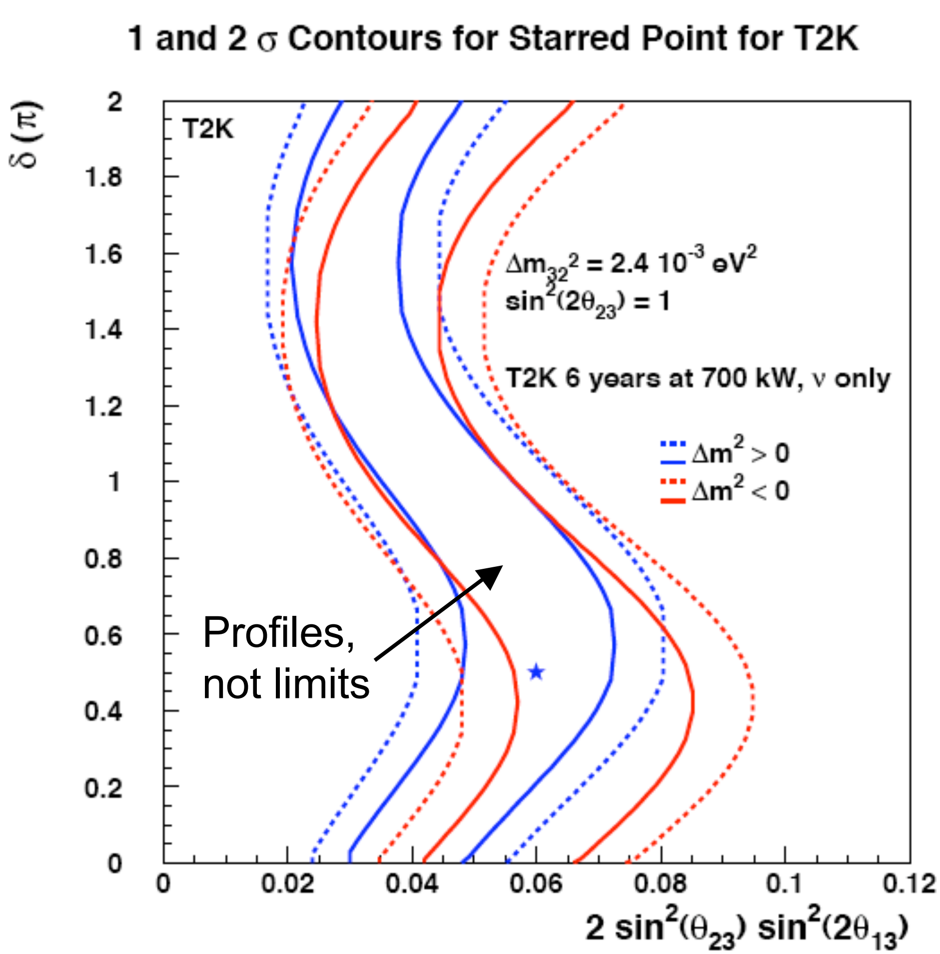
Normal Ordering

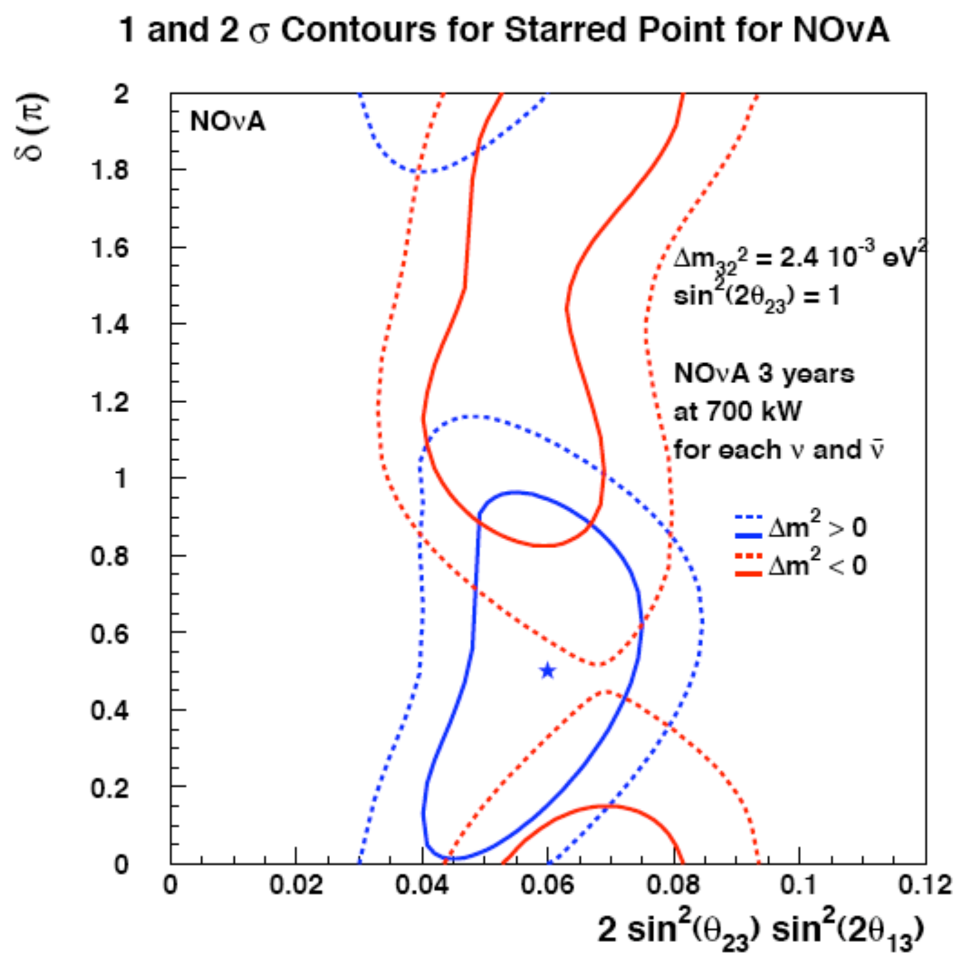
Inverted Ordering

δ vs. θ_{13} Contours: Best Possible δ

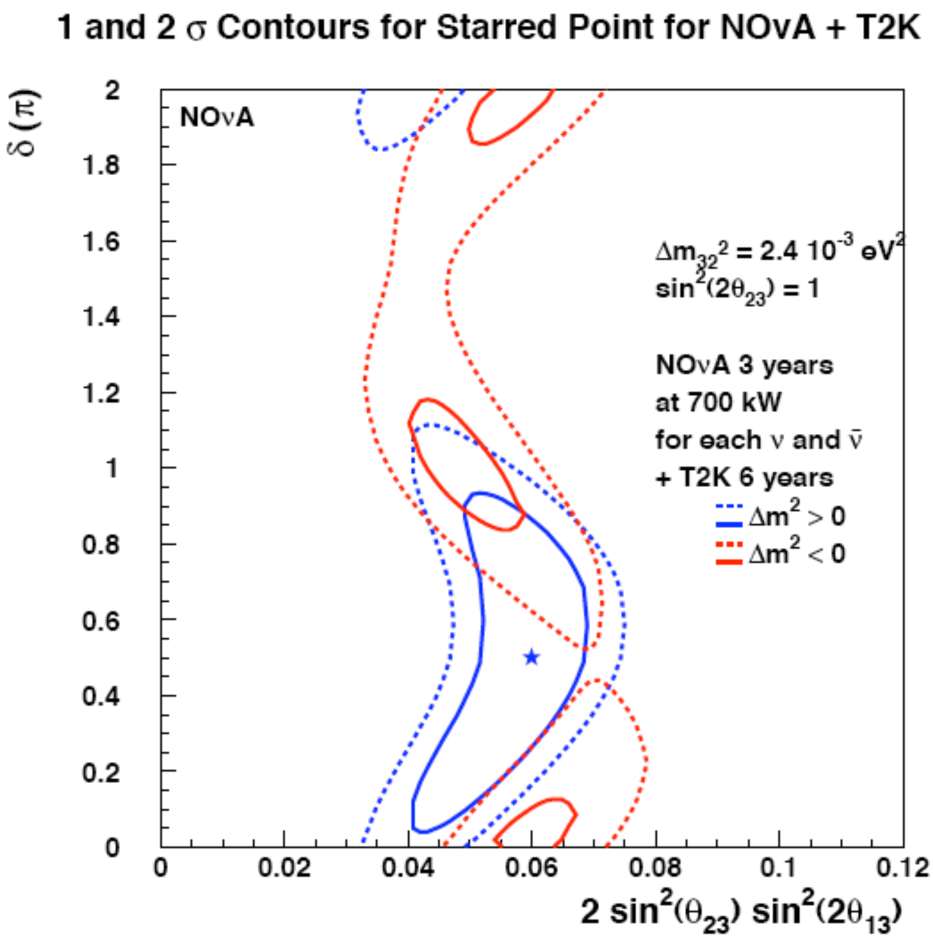


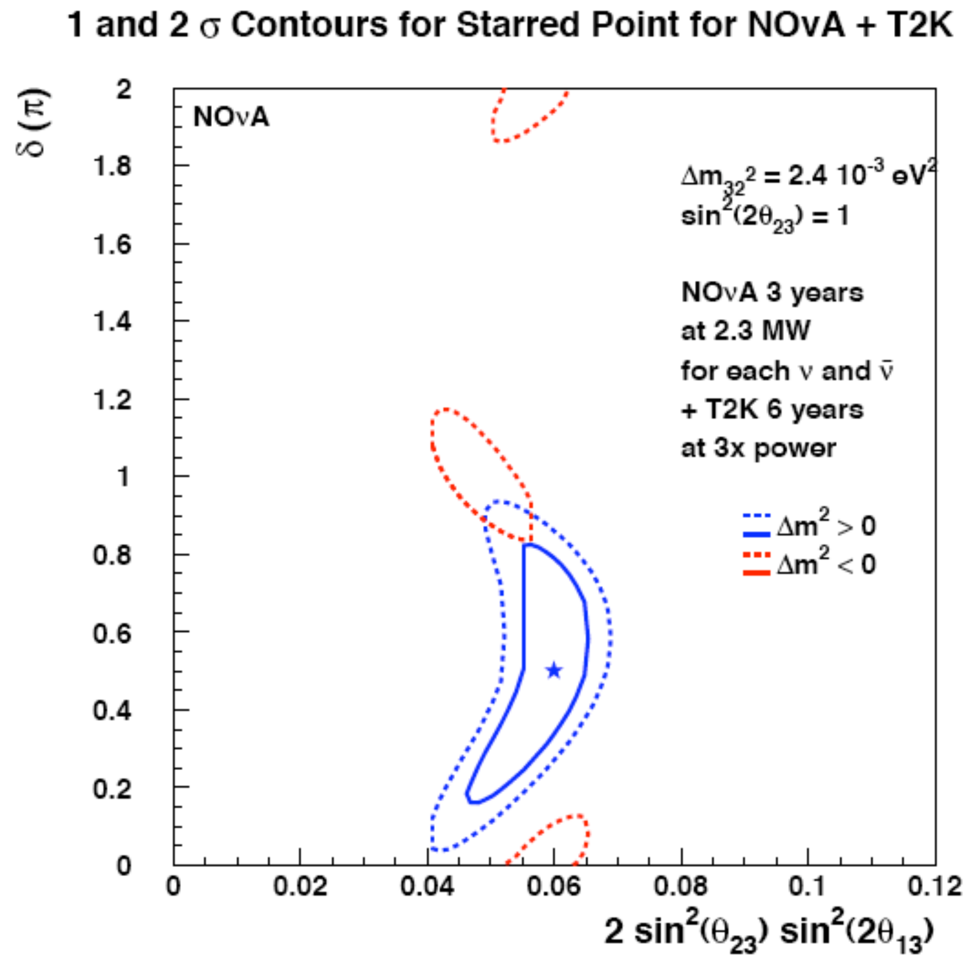
δ vs. θ_{13} Contours: Worst Possible δ T2K and NOνA Alone





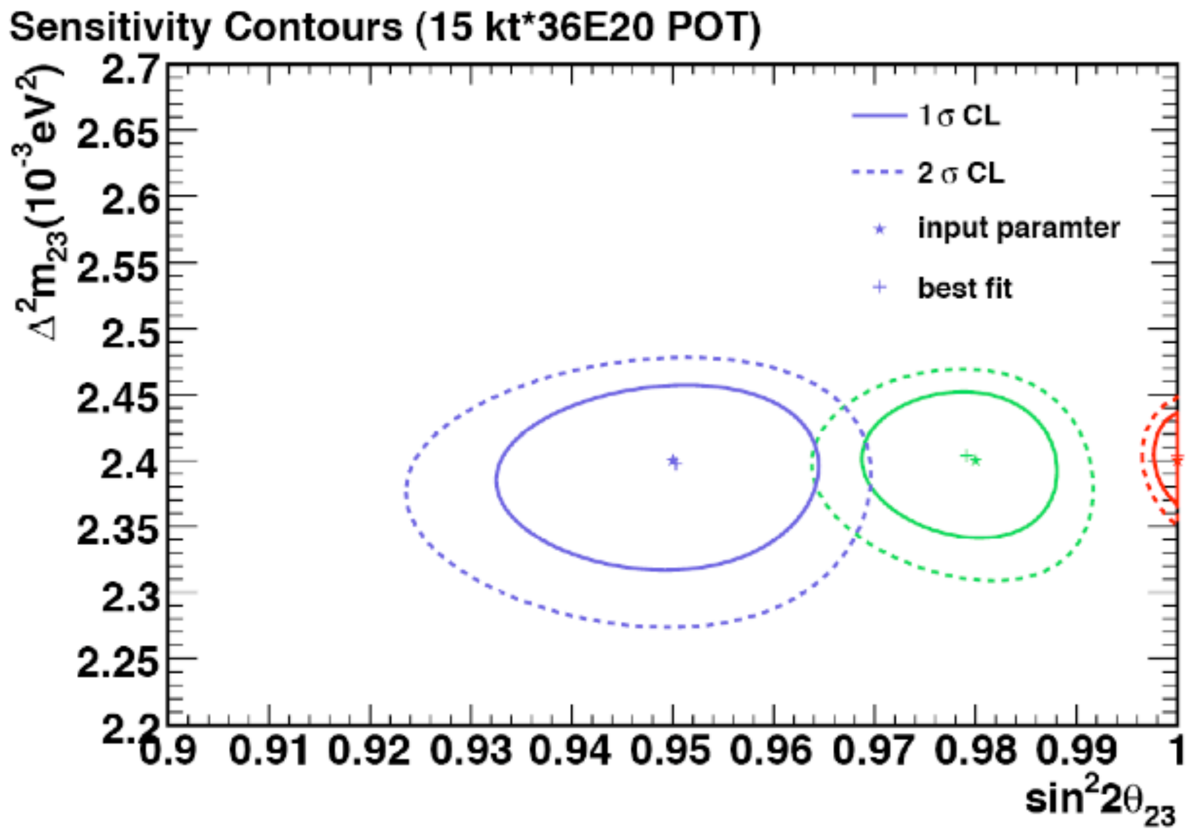
δ vs. θ_{13} Contours: Worst Possible δ T2K and NOνA Combined





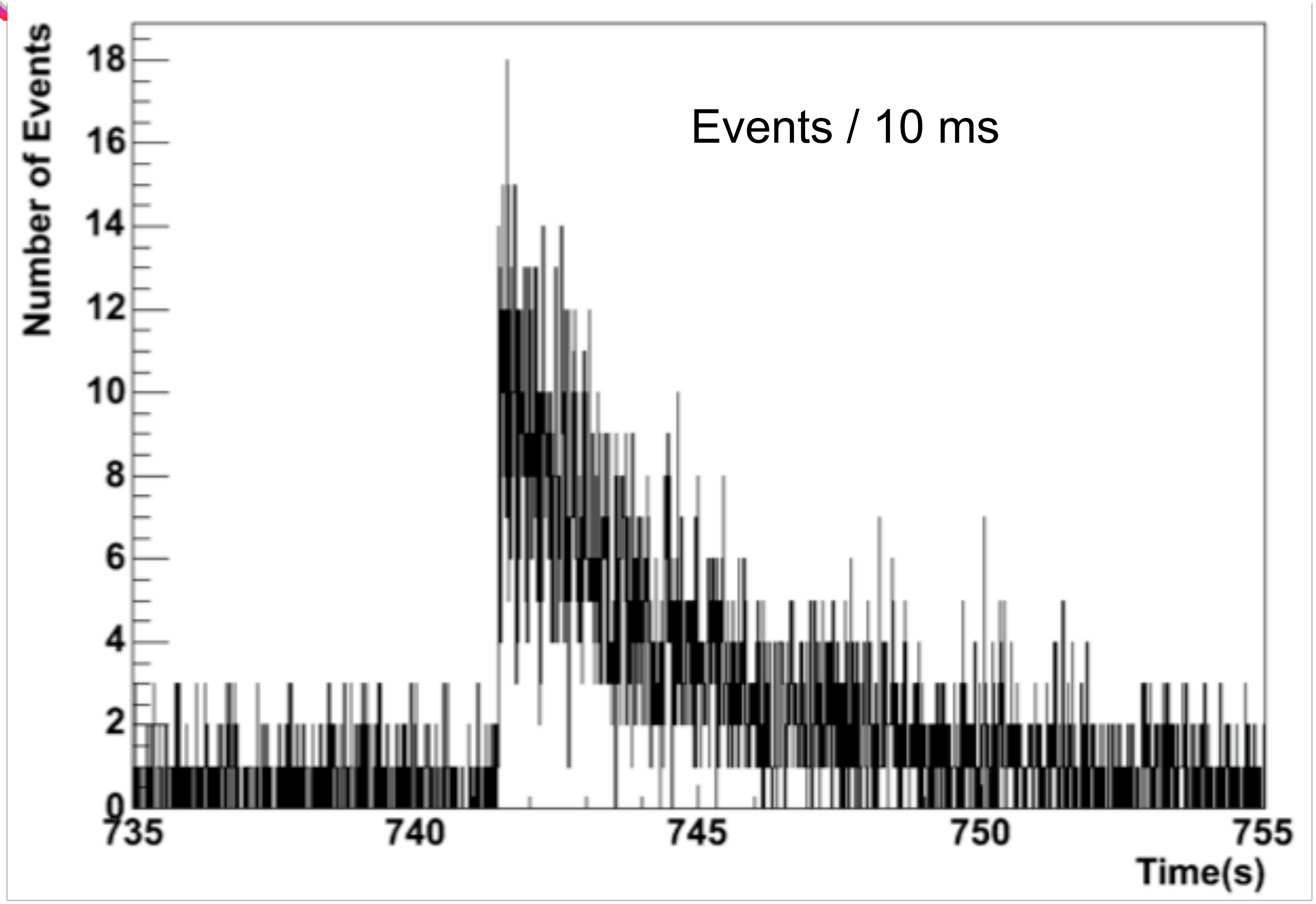
Measurement of $\sin^2(2\theta_{23})$

This calculation uses NOνA's excellent energy resolution on ν_μ CC events.



It is a parameterized calculation, which needs to be redone with a full reconstruction.

Galactic Supernova Signal

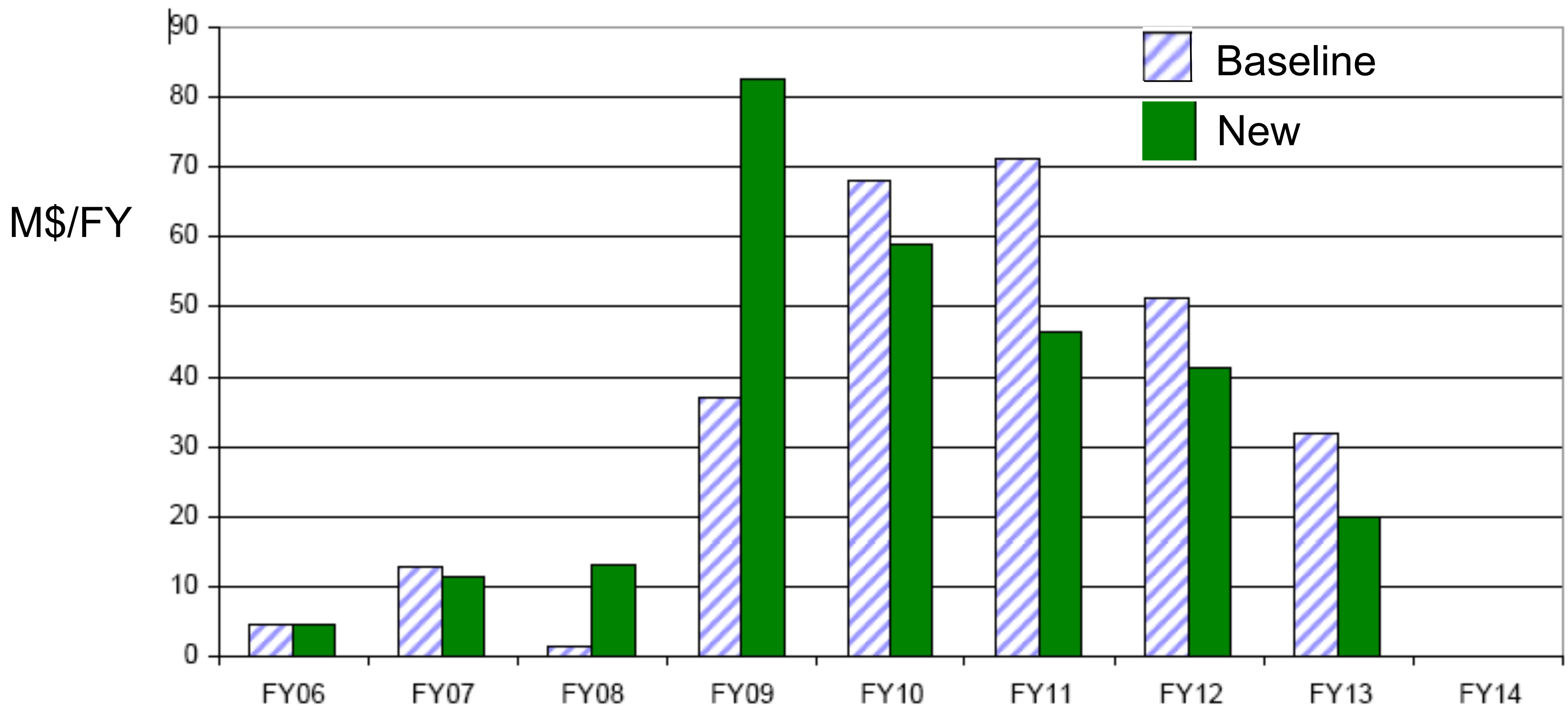


NOνA would see burst of 5000 events for a supernova at the center of the galaxy

Recent NOνA History

- Oct 2007 Passed CD2/3a Review, baselined at \$270M
- Dec 2007 Zeroed out of the Omnibus Funding Bill
- Feb 2008 OHEP asks NOνA to plan for an FY09 start; TPC increased to \$278M for escalation.
- Jul 2008 NOνA receives \$9M in Supplemental Funding Bill. Restart is difficult since personnel have have been assigned to other projects.
- Oct 2008 Start of Continuing Resolution; NOνA funded for partial FY09.
- Mar 2009 NOνA receives \$55M in stimulus funding plus \$28M in regular funding.

Baseline and New Funding Profiles



Response to New Funding

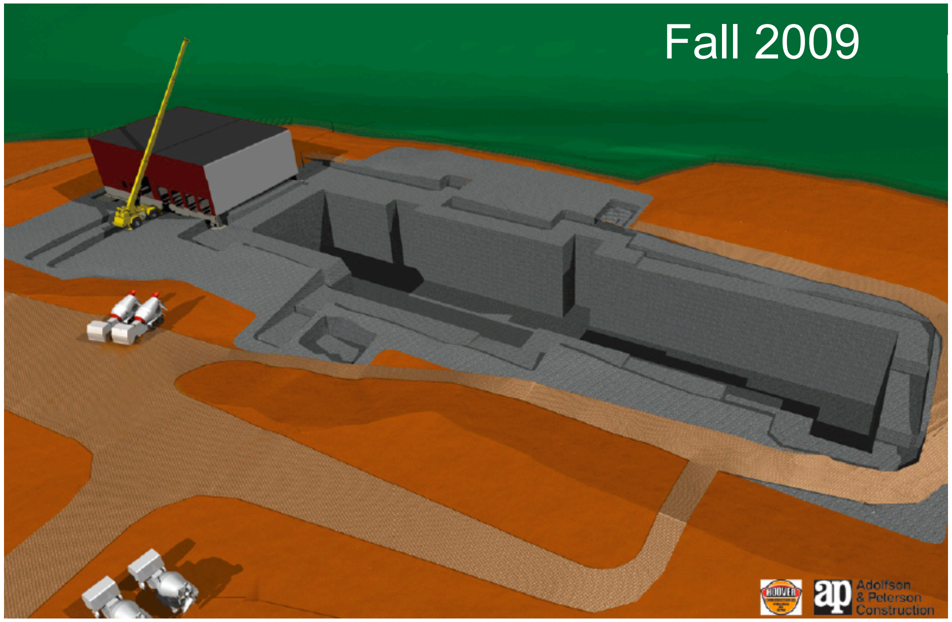
- Contract to build the whole far detector building instead of doing it in phases.
- Build the full near detector and use it as the Integration Prototype Near Detector (IPND)
  - Requires a new enclosure rather than the MINOS surface building.
- Accelerate procurement of "commodities":
  - PVC extrusions
  - Wavelength-shifting fiber
  - APDs
  - Kicker parts

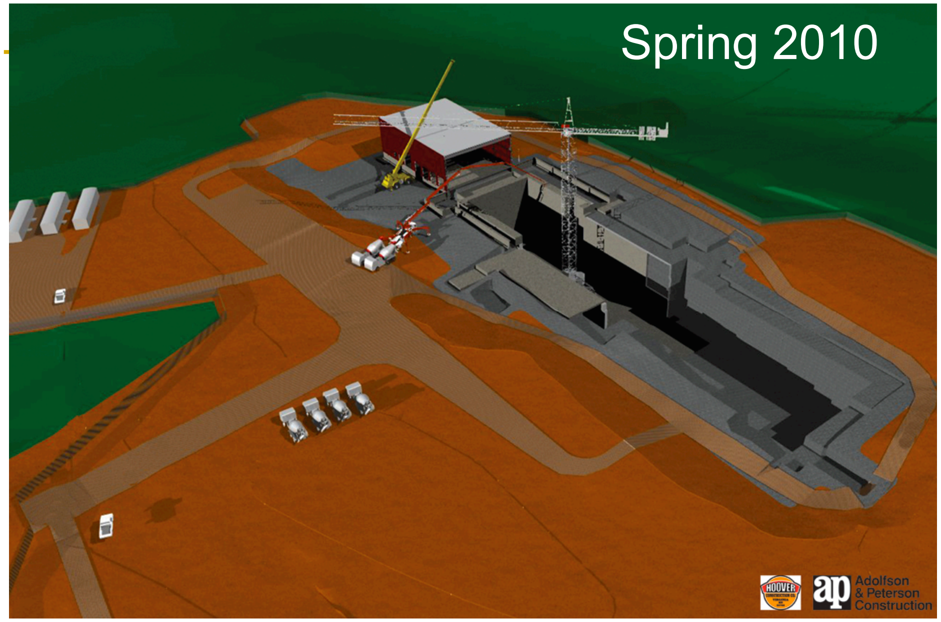
NOνA Ground Breaking
1 May 2009

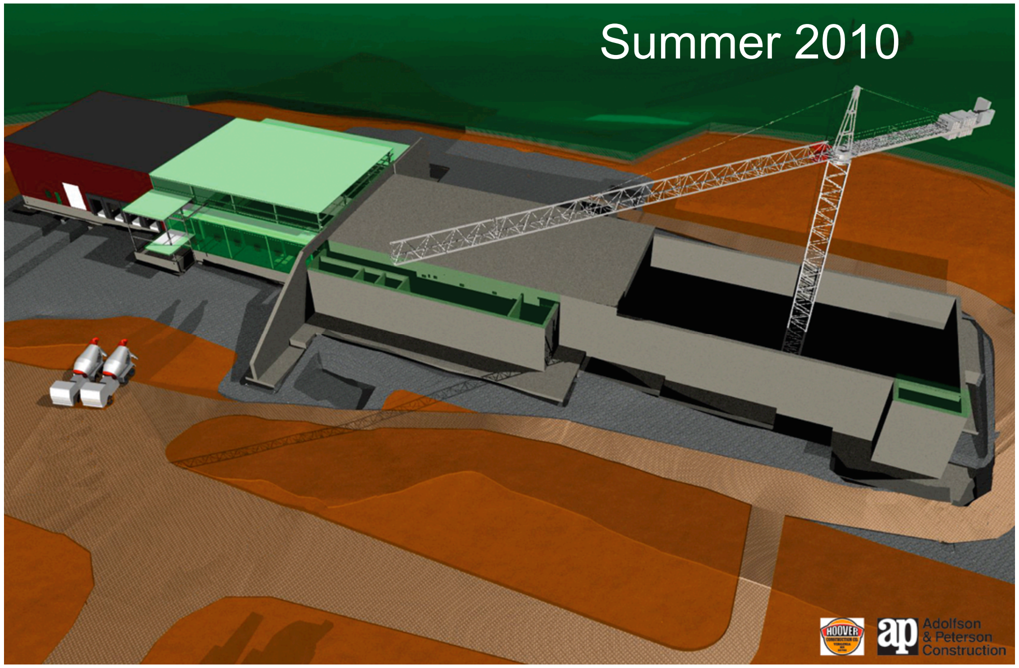
Fermilab Gothic

Reception at Orr

Jim’s Ash Trail Store





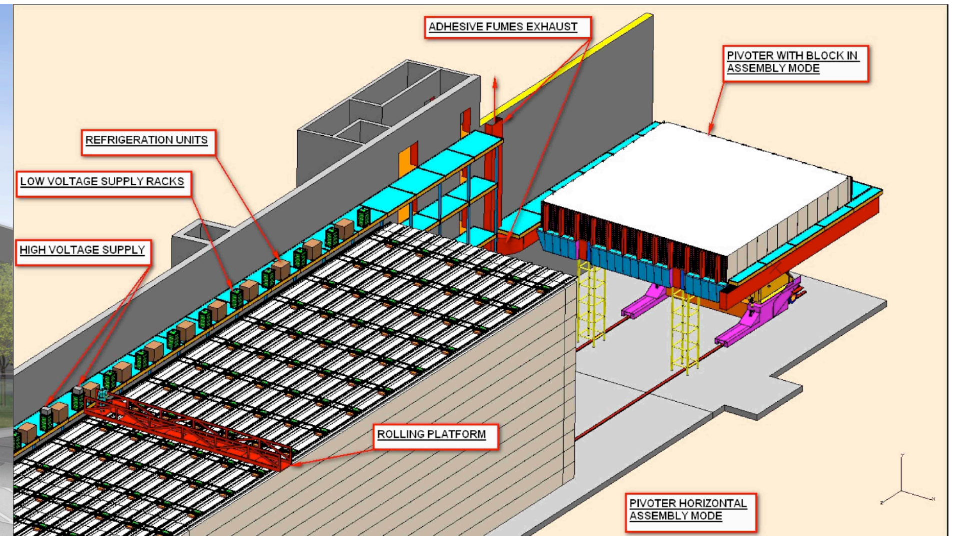


Beneficial occupancy

Assembly area July 2010

Full building November 2010

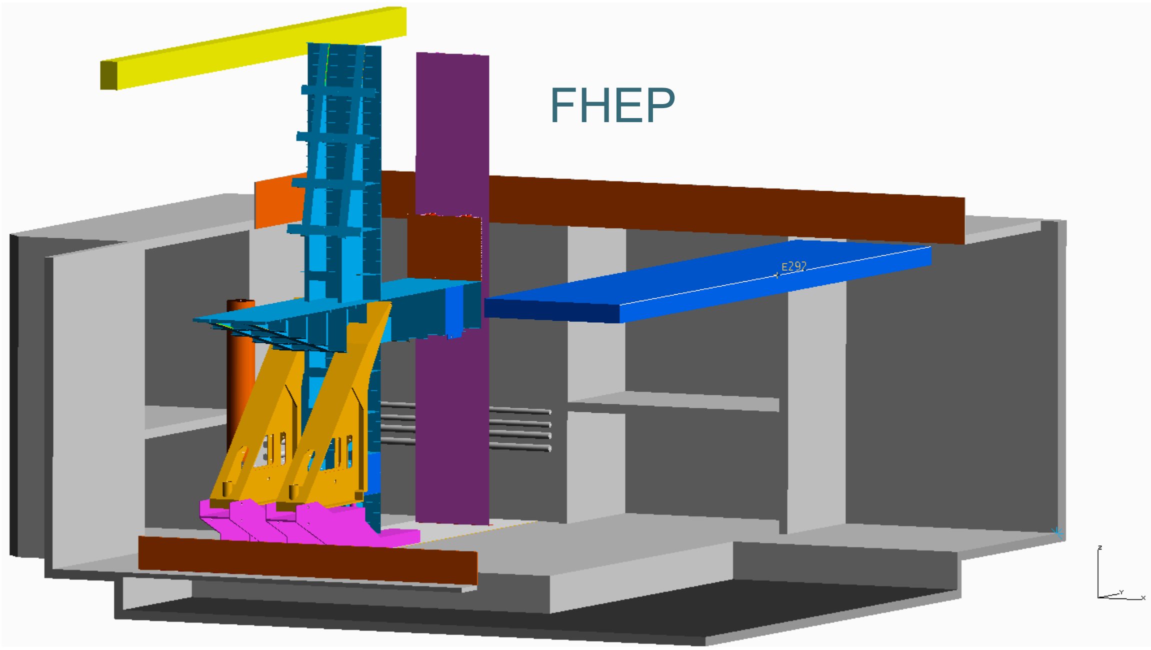
Entrance



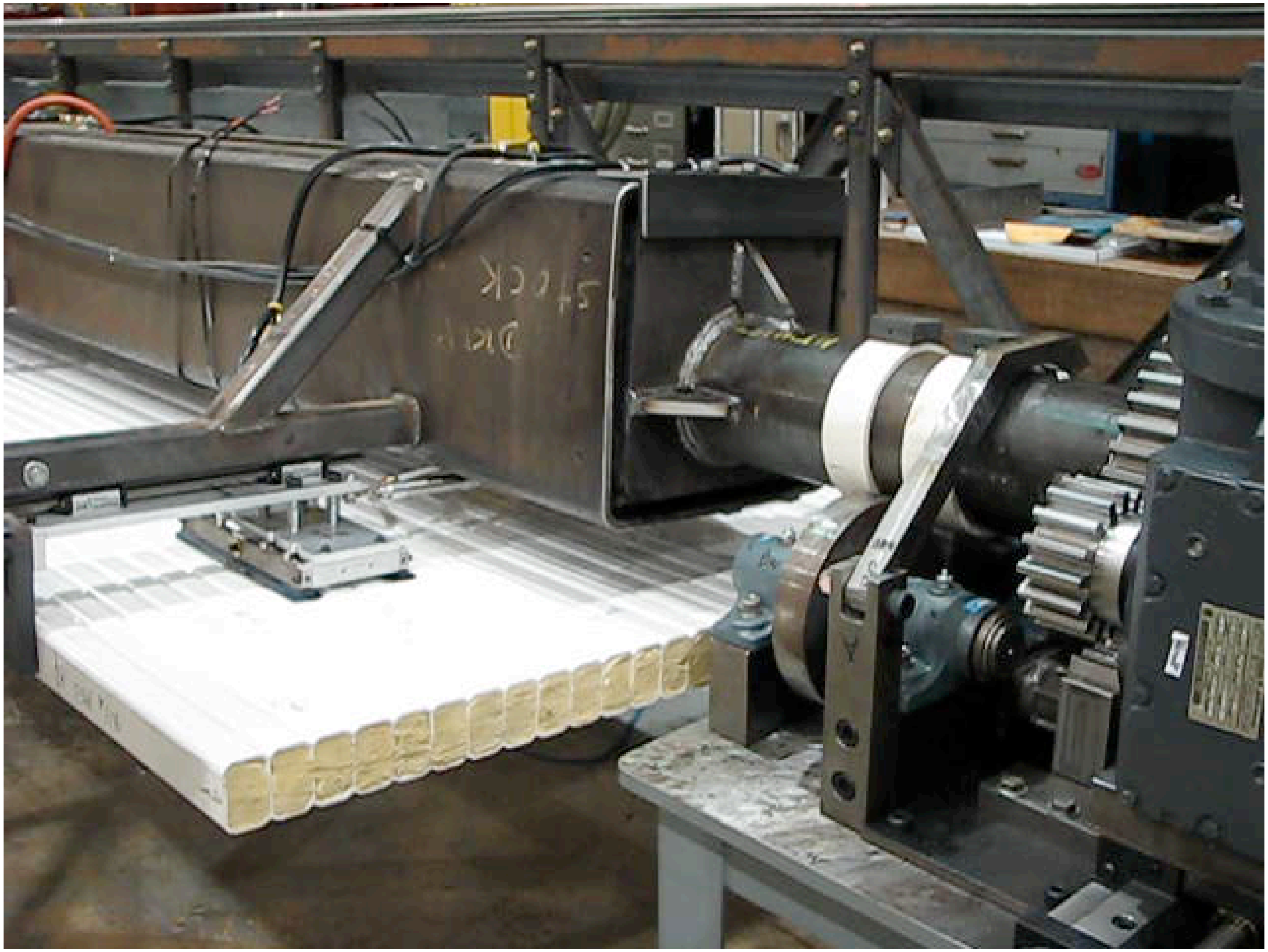
View from the loading dock

Assembly Progress at Argonne

- The current assembly R&D effort is the construction of the Full Scale Assembly Prototype (FSAP) at Argonne.
  - Construction of 6 full size planes for time and motion studies and placement precision.
- Next will be the Full Height Engineering Prototype (FHEP), which will be in the CDF building.
- Then the IPND.



Rotating the module



Adhesive Machine Demo

8 nozzles
will be used
in production.

Collaboration Standing on the FSAP

Reviews

- The Earned Value Management System (EVMS) review was May 11-15.
  - NOνA did well. The outbrief was effusive with praise.
  - Scientists' salary compromise: part of EVMS, but not the TPC.
- CD-3b Director's review last week. It went very well.
- CD-3b DOE review July 21-23.

Probable Schedule

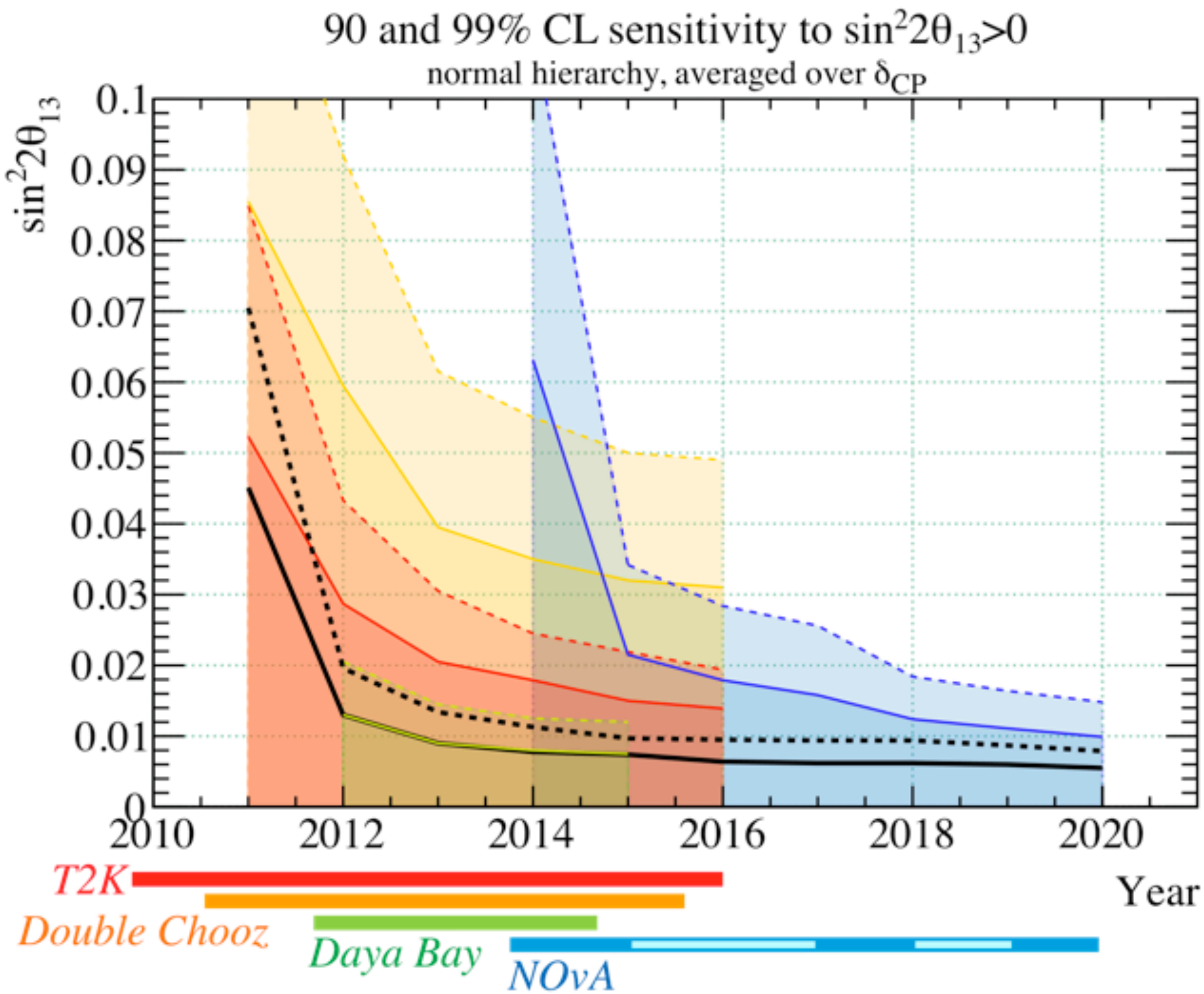
IPND operational	Spring 2010
Far detector building complete	Nov 2010*
Start of far detector assembly	Sep 2011
Start of long shutdown for NuMI upgrades (determined by Collider run)	Oct 2011
First 2.5 kT operational	Jan 2012*
Full far detector operational	May 2013*

*We will try to accelerate these items by 6 months.

Backup Slides


Image from Google

Progress toward $\theta_{13} > 0$



Mass Hierarchy